SSRG International Journal of Civil Engineering
ISSN: 2348-8352/ https://doi.org/10.14445/23488352/IJCE-V13I5P115

Volume 13 Issue 5, 222-249, May 2026

Original Article

Use of Nopal Mucilage, Chia, and Tara Gum for Stabilizing Liquid Soils

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Received: 20 February 2026 Revised: 6 April 2026 Accepted: 22 April 2026 Published: 29 May 2026

Abstract - *Soil liquefaction is one of the most critical phenomena associated with moderate and severe earthquakes, due to the abrupt loss of strength and stiffness in saturated sands, causing settlement, lateral displacement, and structural failure. Given that conventional stabilizers have environmental limitations, this research evaluated sustainable alternatives based on Nopal Mucilage, Chia Mucilage, and Tara Gum applied to poorly graded Sandy Soil (SP) in the Pilcomayo sector, characterized by a shallow water table and high vulnerability to liquefaction. The soil was classified as poorly graded sand with gravel (SP) after granulometric, limit, and compaction tests. Specimens were prepared with this material and treated with biopolymers in different dosages: Nopal Mucilage at 4%, 6%, 8%, 10%, and 12%; Chia Mucilage at 1%, 1.5%, 2%, 2.5%, and 3%; and Tara Gum at 0.2%, 0.3%, 0.4%, 0.5% and 0.6%. After 28 days of curing, static and cyclic triaxial CU tests were performed to evaluate resistance and susceptibility to liquefaction. The results showed that tara gum achieved its best performance at 0.4%, achieving balanced increases in cohesion, friction angle, allowable capacity, and number of cycles to liquefaction, as well as lower pore pressures. Nopal mucilage, particularly at 10%, showed the greatest improvements in static strength, increasing cohesion, and allowable capacity. Chia mucilage, with the best response at 2%, effectively reduced the development of pore pressure under cyclic loads. Overall, the three biopolymers proved to be viable, economical, and eco-efficient natural additives capable of improving the dynamic behavior of sands and reducing their susceptibility to liquefaction.*

Keywords - *Natural Biopolymers, Soil Liquefaction, Mucilage, Tara Gum, Triaxial Test.*

1. Introduction

Globally, soil liquefaction is one of the most critical geotechnical phenomena associated with the occurrence of medium and large magnitude earthquakes [1]. This process mainly affects deposits of loose sand, sandy silt, and poorly compacted fill, which, under saturated conditions, suddenly lose their shear strength and stiffness, behaving in a similar way to a fluid [2]. Its effects include differential settlement, lateral deformation, and severe damage to buildings and infrastructure, generating significant social and economic risks in urban and rural areas [3, 4]. Figure 1 shows representative cases. In item a, the Christchurch earthquake in New Zealand on 22 February 2011, with a magnitude of 6.2 Mw, caused widespread liquefaction in sandy soils with a shallow water table, leading to sand boils, differential settlement, and lateral spreading of the ground, with more than 15,000 homes damaged, more than half of which were beyond repair [5]. In item b, the 7.5 Mw magnitude earthquake that struck Sulawesi, Indonesia, on 28 September 2018 caused liquefaction in alluvial deposits and saturated sandy soils, triggering massive lateral landslides that swept away entire neighborhoods, displaced homes hundreds of meters, and buried thousands of people, causing more than 4,000 deaths and severe damage to infrastructure [6]. In item c, the Kahramanmaraş earthquake in Turkey in February 2023, with a magnitude of 7.8 Mw, caused liquefaction in extensive saturated alluvial areas, resulting in differential subsidence, longitudinal cracks, and the partial or total collapse of dozens of buildings in the city of Antakya, with a high number of casualties and victims [7]. As for Peru, in item d, the earthquake in southern Peru on 23 June 2001 with a magnitude of 8.3 Mw caused liquefaction in alluvial deposits in Moquegua, Arequipa, and Tacna, generating settlements and lateral displacements that destroyed roads, bridges, and riverside dwellings, as well as the failure of a recently constructed bridge pillar [8, 9]. Finally, in item e, the Pisco earthquake in Peru on 15 August 2007, with a magnitude of 8.0 Mw, caused liquefaction in saturated alluvial and marine deposits, resulting in differential settlements of up to 0.9 metres, lateral displacements of approximately 3 kilometres, sand eruptions and severe damage to homes, on the Pan-American Highway South, the port of San Martín, and hospitals, where partial collapse of wards was recorded [10]. The examples presented indicate that soil liquefaction represents a critical threat within the field of geotechnical engineering, and the case of Peru illustrates how sedimentary structures can increase the likelihood of structural damage. In this regard, it is essential to explore more sustainable soil stabilization mechanisms as alternatives to cement and synthetic polymers, which, although effective in stabilizing soils, entail negative environmental and economic impacts [11, 12]. On the other hand, the use of biopolymers constitutes an innovative approach compared to conventional soil stabilizers, particularly as recent studies indicate that these materials can significantly enhance both the strength and liquefaction resistance of cohesionless soils, such as sands and silty soils. Research findings have shown that the addition of 2% agar to sand increased the number of cycles required to induce liquefaction by more than four times, while silty sand achieved up to 61 cycles compared to 19 cycles with the incorporation of guar gum. This suggests that biopolymers may represent an environmentally efficient alternative [13]. That is why this research proposes to evaluate biopolymers that have not yet been directly applied to liquefiable soils. To begin with, nopal mucilage exhibits a unique composition of hydrophilic polysaccharides and minerals, including calcium and potassium, resulting in a high-viscosity structure that retains water and exerts a binding effect that restricts the mobility of interstitial water, thereby increasing the shear strength of saturated sands [13]. Furthermore, chia mucilage forms a colloid with a carbohydrate-protein structure that provides gelling, film-forming, and stabilizing properties of fine particles, reducing their dispersion, supporting aggregate stability, and modifying the soil pore size distribution to increase microporosity [14]. Finally, tara gum, a galactomannan polysaccharide with high viscosity, has been shown to enhance cohesion, reduce water-induced erosion, and improve the compressive strength of soils when combined with granular and fine particles [15]. In contrast, the methods and biopolymers studied for incorporating natural additives to stabilise soil liquefaction are limited. Most global research has focused on the use of synthetic polymers, particularly sodium polyacrylate, superabsorbent polymers, and laponite suspensions, with relatively few studies on biopolymers. Although these materials reduce liquefaction susceptibility and improve mechanical performance, they are not economically viable for widespread application. Currently, in Peru, there are no records of the use of biopolymers in granular soils susceptible to liquefaction, indicating that there remains significant scope for further investigation into this method. To address this limitation, this research evaluates nopal mucilage, chia mucilage, and tara gum, the materials that have not yet been utilized in liquefiable soils, and analyses them through consolidated and unconsolidated cyclic triaxial tests, both static and cyclic, under anchored conditions. In this way, the study provides new experimental data regarding their impact on the mechanical behavior and liquefaction resistance of granular soils in the Peruvian context.

Fig. 1 Cases of soil liquefaction

2. Literature Review

Soil stabilisation has been extensively investigated to enhance the mechanical properties and reduce the liquefaction susceptibility of granular soils. Recent studies have explored the use of synthetic polymers and biopolymers as alternative stabilising agents, demonstrating significant improvements in strength, durability, and performance under static and cyclic loading conditions.

2.1. Conventionally studied biopolymers

Researchers from the Department of Civil Engineering at the Islamic Azad University of Iran have begun investigating biopolymers such as guar gum and agar gum, and their effects on mechanical properties, cohesive strength, and liquefaction resistance of sand and loose siliceous sand. For this purpose, siliceous sand and natural sand were obtained from the northern region of the country, and test specimens were prepared by incorporating biopolymers at different concentrations (0.5%, 1%, and 2% by dry soil weight) using the wet mixing method.

The specimens were compacted to 95% of the maximum dry density, cured for 28 days, and subsequently subjected to Unconfined Compressive Strength (UCS) tests, direct shear tests, Unconsolidated Undrained (UU) triaxial tests, Ultrasonic Pulse Velocity (UPV) tests, as well as consolidated and unconsolidated Cyclic Triaxial (CU) tests. The results showed a considerable increase in strength. The UCS of untreated soil was nearly zero, whereas with 2% agar gum, the UCS reached 2373 kPa for sand and 3186 kPa for siliceous sand. In addition, liquefaction resistance improved significantly. With the addition of 2% agar gum at a Cyclic Stress Ratio (CSR) of 0.20, the number of cycles required to induce liquefaction in sand increased by 440%, demonstrating that 2% agar gum is an effective and environmentally friendly stabilizer [16].

2.2. Synthetic Polymers for Soil Stabilisation

On the other hand, researchers from the Department of Civil Engineering at Eskişehir Technical University in Turkey seek to improve sandy soils in that country in order to prevent liquefaction under critical conditions. The study evaluated the use of Sodium Polyacrylate (SPA) in gel form as the main additive, supplemented with a maximum proportion of 25% cement relative to the dry weight of the SPA (equivalent to 0.2% in gel form) to improve the stability of the material. SPA was applied in proportions ranging from 2.5% to 20% in poorly graded silica sand, both in the dry state and in gel mixture.

Representative results showed that the addition of 5% gel increased soil cohesion to 24.87 kPa (from 0 in natural soil) and increased the angle of internal friction by 1.8 times compared to the condition without the additive, reaching 45° at 20% gel. In addition, a notable reduction in permeability was obtained (from 0.015 cm/s to 0.012 cm/s with 15% gel) and a high swelling potential of up to 940%, which showed that SPA-cement significantly improves the shear strength, stiffness, and bearing capacity of liquefiable soils [17].

In Poland, researchers from the Institute of Environmental Engineering at the Wrocław University of Environmental and Life Sciences conducted research to analyse the swelling behavior of Superabsorbent Polymers (SAP) applied as soil amendments under different loading conditions. A cross-linked copolymer of acrylamide and potassium acrylate (Aquasorb 3005 KL) with a particle size of 0.5 to 3.15 mm was used in 2 g samples subjected to loads equivalent to soil layers of 10, 20, and 30 cm with densities of 0.5, 0.9, and 1.3 g/cm³, representing stresses from 0.49 to 3.83 kPa. The results showed that the absorption capacity decreased significantly under load: while the unloaded sample reached an equilibrium of 338.5 g/g of water absorbed in 63 minutes, with the maximum load of 3.83 kPa, the swelling was reduced to only 19.3 g/g and the time to reach 63% of maximum absorption was extended to more than 300 minutes. Even under intermediate load conditions (20 cm of soil with $\rho = 0.9$ g/cm³, 1.77 kPa), absorption was limited to 26.9 g/g, well below the control capacity. This demonstrates that soil pressure not only reduces the volume of water retained by Superabsorbent Polymers (SAPs) but also significantly prolongs their swelling kinetics, which is of critical importance for the overall evaluation of their efficiency in agricultural and environmental applications [18].

Investigations conducted by Xi'an Jiaotong University and Tongji University (Shanghai) on Hostun sand modified with 5% laponite suspensions reported contents of 1.6% and 1.52% by dry weight of the specimens at relative densities (Dr) of 50% and 60%, respectively. After one week of curing, liquefaction resistance in both cyclic triaxial and centrifuge tests nearly doubled compared to that of clean sand, resulting in reductions of up to 49% in tunnel uplift and 57% in surface settlements [19].

As part of the European LIQUEFACT project, researchers from the University of Bologna, Department of Civil Engineering, modified Leighton Buzzard sand using laponite suspensions at concentrations of 1.5% and 3%, together with sodium pyrophosphate (0.03% to 0.06%) to control gelation time. The mixtures demonstrated a satisfactory level of injectability, and with only 1% laponite by dry weight, cyclic resistance increased by more than threefold: specimens treated at a Cyclic Stress Ratio (CSR) of 0.135 liquefied after 38 cycles, whereas untreated sand liquefied after 12 cycles [20].

2.3. Natural Biopolymers: Nopal, Chia, and Tara

Natural biopolymers are less harmful to the environment and more effective in improving soil properties than synthetic polymers. The following subsections provide further details on their respective contributions.

2.3.1. Nopal Mucilage

In Nigeria, researchers at Covenant University conducted applied research on the use of nopal (Opuntia ficus-indica) mucilage as a natural additive for stabilizing lateritic soil classified as A-2-6 according to the AASHTO system. For the study, fresh nopal cladodes were collected, from which the mucilage was extracted by maceration in water, obtaining a viscous solution that was then mixed with the soil in proportions of 0%, 4%, 8% and 12% by weight relative to the dry soil. These mixtures were used to prepare stabilized soil specimens, and their physical and mechanical properties were evaluated, including Atterberg limits, expansivity, permeability, Unconfined Compressive Strength (UCS), and CBR index in wet and dry conditions. The results showed that as the mucilage dosage increased, the plasticity, permeability, and expansivity of the soil decreased, while the CBR showed significant increases in all conditions evaluated. The optimal dosage was 8%, at which the soil, which initially only met specifications for use as subgrade, met the requirements for use as subbase material in pavements. In conclusion, the study verified that nopal mucilage acts as a natural modifier of soil engineering properties, constituting an ecological, economical, and sustainable alternative to conventional stabilizers [13].

In Mexico, researchers from the Autonomous University of Tamaulipas (Faculty of Architecture, Design and Urbanism) conducted research on the use of nopal mucilage and aloe vera extract as natural stabilizers in lightweight concrete with volcanic tuff and expanded clay aggregates. To do this, they collected 2.8 kg of nopal cladodes and 2.3 kg of aloe vera leaves, which were cut into 2 cm pieces, macerated in distilled water (ratio 1:10 kg/L for 24 h), and then filtered to obtain the viscous extract. A concentration of 1035.42 ± 27.88 mg/L was determined for the nopal mucilage and 526.25 ± 11.92 mg/L for the aloe vera. With these additives, six experimental lightweight concrete mixtures were designed (LCAT, LCNT, LCST, LCAAE, LCNAE, and LCSAE), partially replacing the water with mucilage or aloe, and the coarse aggregate with volcanic tuff or expanded clay. The results showed that nopal mucilage, when combined with expanded clay (LCNAE), achieved a compressive strength of 11.447 MPa and good thermal retention (resistivity of 206.23 °C·cm/W), superior to the mixture with tuff (9.503 MPa). In contrast, when used with tuff (LCNT), the concrete became less workable and less resistant, although with better permeability control. In thermal terms, the mucilage favored heat retention and insulation, making it a promising additive for sustainable and energy-efficient concrete [21].

In Mexico, researchers at the National Technological Institute conducted applied research on the use of nopal (Opuntia ficus-indica) mucilage as a natural waterproofing agent to reduce humidity in homes in Valle de Bravo. For the study, 3,141.5 g of nopal cactus pads were collected and macerated in water in a 1:2 ratio (nopal: water) for 48 hours, obtaining a viscous extract filtered through No. 8 and No. 100 mesh screens. Three waterproofing mixtures were prepared with this mucilage: Test 1: 200 ml of mucilage + 300 ml of water + 100 g of lime + 70 g of alum stone + 60 g of neutral soap. Test 2: 300 ml of mucilage + 400 ml of water + 70 g of alum. Test 3: 300 ml of mucilage + 400 ml of water + 150 g of lime + 60 g of salt. These formulations were applied to red fired clay bricks (7×14×28 cm) in two coats with a brush, and their behavior in terms of water absorption was evaluated according to the Mexican standard. The results showed that Test 1 was the most efficient, reducing absorption to an average of 4.33%, followed by Test 3 with 6.83% and finally Test 2 with 7.50%, compared to the unwaterproofed brick, which reached 14% absorption. In conclusion, it was verified that nopal mucilage, combined with lime, soap, and alum, better seals the pores of bricks and acts as a protective coating against moisture and saltpeter, constituting an ecological, economical, and sustainable alternative to industrial waterproofing agents [22].

In Tunisia, researchers at Tunis El Manar University conducted research into the development of an environmentally friendly lightweight concrete using nopal (Opuntia ficus-indica) fibers as reinforcement. To do this, they collected fibers from cladodes and dry prickly pear trunks from the Tunis region, which were cut into 2×2, 3×3, and 5×5 cm sheets with an average thickness of 0.9 mm and pre-treated in hot water to improve their adhesion. These fibers were incorporated as a partial substitute for sand and gravel in proportions of 5, 10, and 15 kg/m³, producing different concrete mixtures together with sand (0/2.5 mm), gravel (4/12 mm), Portland cement type CEM I 42, and water. The study compared the physical, mechanical, and thermal properties of these mixtures with a reference concrete without fibers. The results showed that, although the addition of fibres reduced compressive strength (from 32 MPa in the reference concrete to 22.8 to 24.2 MPa with 15 kg/m³, i.e. a decrease of 24 to 29%), it produced notable improvements in other properties: flexural strength increased by between 135 and 156% at 28 days, density decreased by more than 25%, resulting in lighter concrete, and thermal conductivity was reduced by up to 42% with 15 kg/m³ of fibres, thus increasing its insulating capacity. In addition, there was a moderate increase in shrinkage (18% more than the control) and a 40% reduction in the dynamic modulus of elasticity, without exceeding the recommended limits for concrete with vegetable fibers. In conclusion, the authors verified that nopal fibers allow for the production of lightweight, insulating concrete with high flexural strength, although with lower compressive strength, making it a sustainable and low-cost alternative for non-structural construction applications where thermal insulation and weight reduction are prioritized [23].

A literature review on the use of nopal (Opuntia ficus-indica) mucilage as a bioadditive in construction materials, particularly Portland-based materials, is presented. The authors of a review analyze the use of nopal mucilage (Opuntia ficus-indica) as a bio-admixture in construction materials, particularly those based on Portland cement. Furthermore, mucilage is biodegradable, biocompatible, and non-toxic, while also being low-cost, capable of retaining water, and able to modify the viscosity and cohesion of mixtures. In construction applications, the review confirms that mucilage enhances the mechanical strength, rheological behaviour, and durability of lime-based products, Portland cement concrete, and compressed earth blocks, acting as a natural substitute for chemical admixtures. The authors acknowledge that the available studies remain inconclusive, and further research is required to advance the understanding of the biocomposite composition and associated construction techniques [24].

2.3.2. Chia Mucilage

Chia seed mucilage (Salvia hispanica L.) has been investigated as a natural soil conditioner by researchers at the University of Basilicata in Italy. Black chia seeds were hydrated, dried, and sieved to obtain a powder containing 44.8% organic carbon. This material was incorporated at proportions of 2% and 10% into sandy silt, silt, and sandy clay soils. Mercury intrusion porosimetry and BET analysis showed that total porosity decreased following the addition of mucilage, mainly due to a reduction in macropores (>10 μm), while micropores (<10 μm) and particle contact area increased. Furthermore, the adsorption of agricultural herbicides (MCPA, diuron, clomazone, and terbutilazine) increased significantly, and desorption was almost entirely suppressed (except for slight desorption of terbutilazine) in sandy silt and silt soils, with silt and sandy clay soils exhibiting a more pronounced effect [25].

Subsequently, the same researchers conducted a second, more specific study aimed at evaluating the mucilage extracted from chia fruits and seeds as a natural stabilizer of soil aggregates, which contained 90% organic matter and 40.3% organic carbon. This mucilage was applied in doses of 1% and 2% by weight, and the stability of aggregates was evaluated by wet sieving, together with CO_2 evolution and analysis by Scanning Electron Microscopy (SEM) and spectroscopy. The results showed a dose-dependent increase in aggregate stability, reaching its maximum effect at 2%, which even exceeded the influence of soil texture, achieving increases of up to 2.3 times in loamy and loamy-clay soils, and 4.9 times in loamy-sandy soils compared to the control. In addition, a drastic reduction in fine particles (<0.1 mm) was recorded, from more than 27% in untreated soil to less than 1% with the optimal dose, evidencing the formation of bridges and cohesive films between particles that favoured the generation of stable aggregates [14].

The impact of chia seed mucilage on structural concrete was studied by researchers in Lima, Peru. Chia seeds from Cuzco were harvested, and the mucilage was extracted by processing the seeds using sulphuric acid, a water bath, and filtration. The mucilage sample was dosed at 25%, 50%, and 75% of the cement weight, corresponding to approximately 2.58 kg, 5.17 kg, and 7.75 kg, respectively. These modifications were applied to 54 concrete specimens designed in accordance with NTP 339.033 and ASTM C31 standards, with a target compressive strength of f'c = 210 kg/cm². The specimens were evaluated for workability, durability, temperature control, flexural strength, and compressive strength at 7, 14, and 28 days. Chia seed mucilage has been shown to improve workability and enhance the mechanical strength of concrete. In concrete mixtures, when used at intermediate dosages, it exhibited higher compressive and flexural strength compared to the control mix [26].

2.3.3. Tara Gum

Northwest A&F University in China has conducted applied research on tara gum (Caesalpinia spinosa), contributing to the development of a green polymer for soil stabilisation and mitigation of water-induced erosion. Regarding its preparation, tara gum was chemically modified through graft copolymerisation with acrylic acid and methyl methacrylate, producing a copolymer emulsion, tara-g-polymer (AA-co-MMA). This additive was incorporated into loess and lateritic soil samples at different proportions, with optimal results obtained at dosages of 0.3% and 0.4% by dry soil weight. Using these formulations, erosion resistance tests and simulated rainfall tests were conducted, along with unconfined compression tests. For loess soil, the 0.3% additive resisted more than 30 hours of continuous rainfall, with recorded erosion loss of approximately 2%, whereas untreated natural soil disintegrated within a few hours. The lateritic soil with 0.4% additive achieved a compressive strength of 3.7 MPa, nearly three times higher than that of the untreated soil [15].

In Peru, researchers from the National University of the Altiplano conducted an experimental study to evaluate the effect of nopal mucilage and tara gum on the stabilisation of clay soil with low bearing capacity. To this end, the material was collected in the district of Puno, and mixtures were prepared incorporating different percentages of biopolymers: 2%, 4%, 6%, 8% and 10% nopal mucilage, as well as 0.2%, 0.4%, 0.6%, and 0.8% tara gum in relation to the dry weight of the soil. The specimens were molded under controlled conditions and tested in the laboratory using unconfined compressive strength, direct shear, and standard Proctor tests. Representative results showed that the addition of biopolymers increased the cohesion and shear strength of the treated soil, with the best values being achieved with 8% nopal mucilage and 0.6% tara gum, doses that also reduced the plasticity index and improved the maximum dry density compared to natural soil [27].

2.3.4. Research Gap and Rationale for the Study

Currently, the high susceptibility to liquefaction of sandy and alluvial soils in seismic areas of Peru is one of the main threats to the safety of buildings and infrastructure. Although physical and chemical stabilisation methods have been studied, the use of conventional additives such as cement or synthetic polymers has environmental, economic, and long-term sustainability limitations. In response, recent research has explored alternatives based on natural biopolymers such as nopal mucilage, chia mucilage, and tara gum, which have demonstrated positive effects in improving cohesion, bearing capacity, and resistance to liquefaction. However, most of these studies have focused on agricultural applications or their use in lightweight concrete, with little experimental evidence regarding their specific performance in granular soils susceptible to liquefaction under dynamic stresses. In this context, this research proposes a comprehensive evaluation of the application of nopal mucilage, chia, and tara gum as natural additives for the stabilisation of liquefiable soils in the district of Pilcomayo, Huancayo. The methodology includes the physical and geotechnical characterisation of the soil, the preparation of test specimens treated with different dosages of biopolymers, and the execution of consolidated undrained triaxial tests (static and cyclic CU) to determine the strength parameters, allowable capacity, and resistance to liquefaction. The objective is to identify the optimal range of additions that will increase safety against liquefaction while reducing the environmental impact associated with the use of traditional stabilisers. This represents an effort to provide robust technical evidence for the integration of biopolymers into sustainable civil engineering, aiming to offer an innovative, cost-effective, and easily replicable solution for reducing geotechnical engineering challenges in urban and seismic areas.

3. Materials and Methods

This section outlines the materials and methods used to evaluate the effectiveness of nopal mucilage, chia mucilage, and tara gum in stabilising liquefiable soils. Samples collected from Pilcomayo were characterised through standard geotechnical tests, including particle size distribution, Atterberg limits, specific gravity, density, void ratio, and Proctor compaction. Specimens were then reconstructed using the wet tamping method with different biopolymer dosages and cured for 28 days under controlled conditions. Finally, Consolidated Undrained (CU) triaxial tests, both static and cyclic, were conducted to determine strength parameters and assess liquefaction resistance compared to untreated soil.

3.1. Study Area

Pilcomayo is located on the left bank of the Mantaro River and is a district of relevance for both urban and agricultural activities, mainly due to its location within the valley [28, 29]. In this context, its proximity to the district of El Tambo, where silty sand and poorly graded sand (SM–SP) soils predominate, together with its location on a recent alluvial plain, makes it necessary to carry out a surface-level geotechnical and geological assessment to guide appropriate land use [30]. Figure 2 shows a vulnerable area within Pilcomayo, corresponding to an alluvial plain near the river. This zone, which was previously used almost entirely for agricultural purposes, has undergone significant changes as a result of rapid urban growth, modifying both the landscape and land use. From a geotechnical perspective, the ground presents unfavourable conditions, such as unconsolidated sediments, irregular stratification, and shallow soil profiles. In addition, the absence of engineering works contributes to an increased risk of liquefaction, particularly due to settlement processes [31]. To define the scope of the research, a soil sample identified as SPT-1 was collected from an agricultural area near the river. The exact location of the sampling point was determined using UTM coordinates, corresponding to Zone 18L, 473028 m E and 8668848 m S.

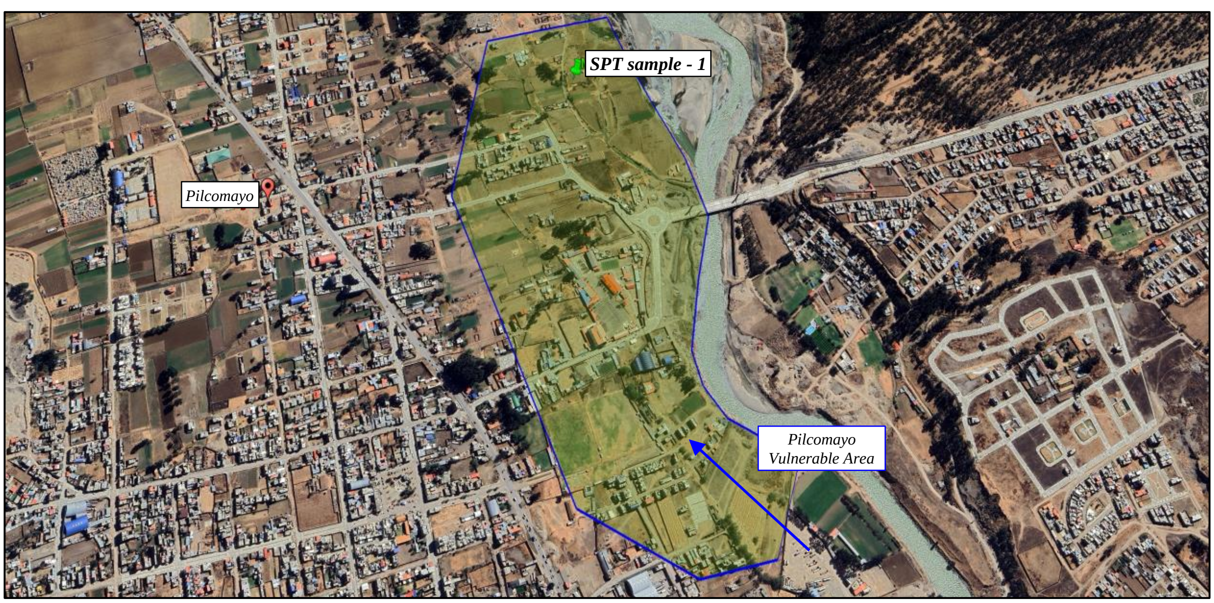

Fig. 2 Study area

3.2. Soil Liquefaction

Liquefaction-prone granular deposits typically consist of loose sands (SP, SM), sandy silts (ML–SM), or poorly compacted fills. During earthquakes of Mw 6.5 or greater, liquefaction increases pore water pressure and reduces effective stress. As a result, soil particles become suspended, causing a loss of stiffness and shear strength and making the soil behave in a fluid-like manner. This phenomenon leads to effects such as differential settlements, lateral spreading, sand boils, and damage to structures founded on these soils [11, 12, 32]. Figure 3 illustrates this process by contrasting stable soil, where the grains remain in contact, with liquefied soil, where increased pore pressure breaks these bonds and triggers ground instability.

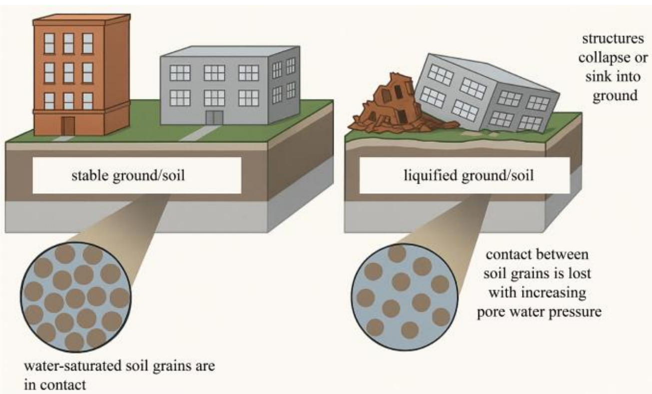

Fig. 3 Soil liquefaction [12]

3.3. Natural Additives

In geotechnical engineering, there is a growing interest in the use of natural biopolymers as an alternative for soil stabilisation. Unlike conventional additives, these organic and biodegradable materials improve the physical and mechanical properties of soil by forming interconnected colloidal networks, thereby increasing strength and reducing fluidity [33].

3.3.1. Nopal Mucilage

Nopal mucilage (Opuntia ficus-indica) is a type of biopolymer composed primarily of a collection of natural hydrophilic biopolymers, mucilage, along with significant amounts of proteins, minerals (Ca, K), phenolic compounds, and fibres. The colloidal structure of the biopolymer and mucilage, containing minerals and proteins, provides high levels of viscosity, absorption, retention, and binding capacity, as well as emulsifying and coating properties, thereby performing most of the cohesive function between particles [24, 34]. These biopolymers and mucilage reduce the mobility of water present within void spaces or pore water and limit the increase in pore pressure, resulting in an improvement in the shear strength of saturated sandy soils. Furthermore, ionic interactions with soil minerals are responsible for the development and stabilisation of microstructures, increasing stiffness and reducing vulnerability to liquefaction-induced instability [21]. For these reasons, mucilage represents a sustainable alternative for soil stabilisation.

Table 1. Properties of Nopal Mucilage

Property	Value	Description
Carbohydrate composition	60% extract by weight	Polysaccharides (arabinose, rhamnose, xylose, galactose, and galacturonic acid) generate a colloidal network that improves the apparent cohesion of the soil [24, 34]
Proteins and phenolic compounds	Protein: 3%	They act as emulsifiers and antioxidants, strengthening the matrix and reducing degradation [34]
Minerals (Ca, K)	Ca and K	They promote ionic bonds with fine particles, help reduce permeability, and improve rigidity [34]
Water absorption capacity	High (46%)	Limits the mobility of interstitial water in saturated soils, reducing the generation of pore pressure [21]
Viscosity of the extract	1035 mg/L in aqueous solution	Its viscous behaviour increases shear resistance in loose sands [21]
Compressive strength in mixtures with nopal	9.5 MPa (with volcanic tuff) 11.4 MPa (with expanded clay)	Indicates cementing effect: improves structural strength and may translate into increased shear strength of the soil [21]

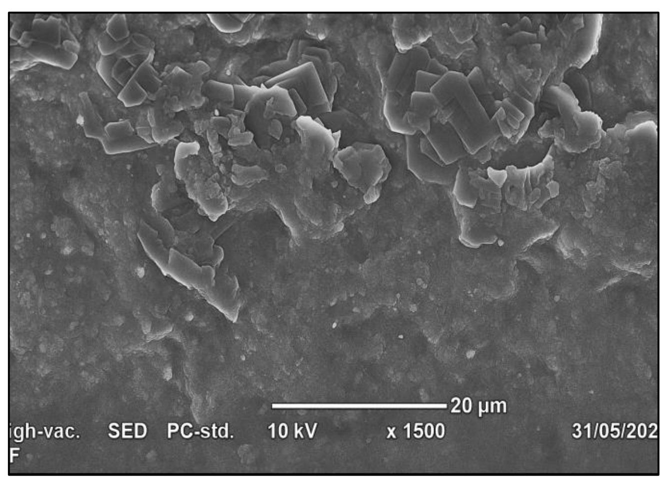

Fig. 1 Mucilage from Opuntia ficus-indica [35]

Based on a review of the literature, it was found that a study that applied Opuntia ficus-indica (nopal) mucilage to lateritic soil classified as A-2-6 the optimal dose was 8% relative to dry soil, as it allowed the soil, initially suitable only as subgrade, to meet the specifications required for use as a pavement subbase, demonstrating the potential of nopal mucilage as a natural modifier of soil engineering properties [13]. Based on this reference value, in this study, nopal mucilage was applied at concentrations of 4%, 6%, 8%, 10%, and 12% in order to experimentally validate its effect on resistance and reduction of susceptibility to liquefaction.

Obtaining Mucilage from Nopal

A controlled procedure was followed to extract the mucilage from the nopal cactus, yielding a biopolymer of high purity and viscosity, suitable for subsequent experimental application. This is a preparation process involving successive maceration and filtration of plant-based materials, as illustrated in Figure 5.

This methodology comprises six sequential steps. (a) Mature cladodes with a dark green and intact epidermis were collected in Pilcomayo, along the banks of the Mantaro River. (b) Cleaning and spine removal were carried out manually using stainless steel tools to prevent contamination and ensure the purity of the material. (c) The cladodes were cut into 1 cm^2 pieces to increase the surface area and facilitate the release of compounds during maceration. (d) An aqueous maceration process was then performed by immersing the sample in distilled water at a ratio of 1:10 (kg/L), allowing it to rest for 24 hours to promote the release of hydrophilic polysaccharides. (e) The material was subsequently subjected to grinding and homogenisation using an industrial blender to obtain a viscous and uniform suspension. (f) Finally, filtration and stabilisation of the extract were carried out, initially using a fine sieve to remove solid fibres, followed by the recovery of the light green, gel-like mucilaginous liquid, which was left to stand for an additional 24 hours to ensure stabilisation prior to its use in experimental testing.

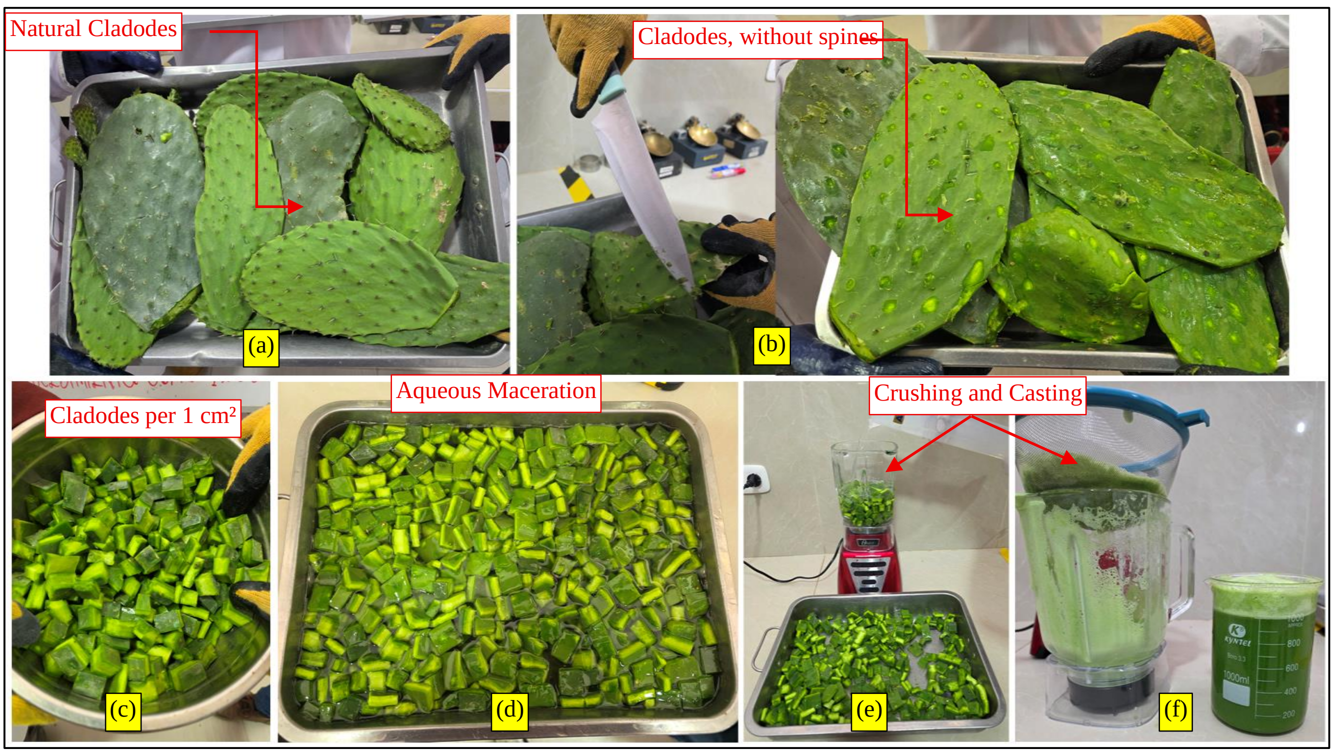

Fig. 5 Obtaining Mucilage from Opuntia Ficus-Indica (Nopal)

3.3.2. Chia Mucilage

Chia mucilage (Salvia hispanica L.) is a natural biopolymer consisting mainly of polysaccharides and a moderate protein fraction, accompanied by minerals, fibre, and bioactive compounds. When hydrated, it releases a gelatinous substance with high water absorption and retention capacity, significant viscosity, and emulsifying and stabilising properties that generate cohesion in dispersed media. Its colloidal structure and protein content give it surface activity and the ability to form films in aqueous systems, although with predominantly viscous behaviour [36, 37]. These characteristics allow the pore distribution in soils to be modified, increasing microporosity and the contact surface between particles, as shown in Figure 6, which reduces the mobility of contaminants and interstitial water. Likewise, the formation of bridges and cohesive films between soil grains promotes stable aggregation, improving structural resistance and reducing erosion and susceptibility to disintegration [14]. The properties mentioned are organised in Table 2.

Table 2. Properties of Chia Mucilage

Property	Value	Description
Carbohydrates	Polysaccharides (>80% of the extract)	Mainly arabinose, xylose, and glucose, which form a colloidal network with high viscosity and water retention capacity [36].
Proteins and bioactive compounds	20% dry matter	It contains moderate amounts of protein, minerals, and phenolic compounds that provide surface activity and antioxidant properties [36].
Minerals (Ca, Mg, K)	Significant presence	They contribute to ionic interactions with fine particles, improving cohesion and reducing soil dispersion [36].
Water absorption capacity	High (rapid gelation, >10 times its weight in water)	It releases a viscous substance with high moisturising capacity, which increases microporosity and limits the mobility of interstitial water [37].
Viscosity of the extract	High (concentration-dependent)	Its viscous behaviour promotes the formation of films and cohesive bridges between particles, improving soil aggregation [37].

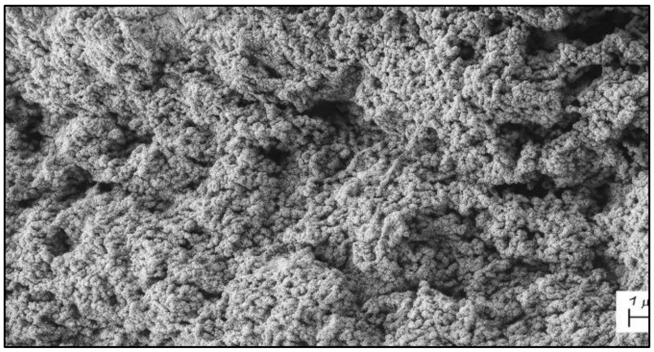

Fig. 6 Chia mucilage (Salvia hispanica L) [36]

Based on a review of the literature, it was found that a study applying Salvia hispanica L. (chia) mucilage to sandy loam, loam, and clay loam soils determined that the optimal dose was 2% by weight of dry soil, as it allowed the effect of texture to be overcome and increased aggregate stability by an average of 2.3 times in loamy and loamy-clay soils, and up to 4.9 times in sandy loam soils, compared to controls without additives [14]. Based on this reference value, in this research, chia mucilage will be applied in a range of 1%, 1.5%, 2%, 2.5%, and 3% in order to experimentally validate its effect on resistance and reduction of susceptibility to liquefaction.

Fig. 7 Obtaining Chia Mucilage

Obtaining Chia Mucilage

Black seeds of Salvia hispanica L. of commercial origin were used to obtain chia mucilage [38], which were processed following a controlled sequence of hydration, drying, and sieving in order to obtain a stable biopolymer of uniform purity. This procedure is shown in Figure 7 and comprised four main phases: (a) seed selection, where uniformity, colouration and absence of impurities were verified, ensuring clean and dry starting material; (b) controlled hydration, in which the seeds were mixed with distilled water in a 1:20 ratio (weight to volume) and kept at 40 °C for 4 hours with constant stirring, allowing the exudation of the mucilage that naturally covers the surface of the seed; (c) drying of the hydrated mucilage, carried out in an oven at a constant temperature of 50 °C for approximately 48 hours, until a solid, dry and stable material is obtained; and (d) sieving of the final product through a number 60 mesh screen, in order to remove seed residues and obtain a fine, homogeneous powder of dry mucilage. Finally, the dry mucilage was incorporated into the soil as a natural amendment, subsequently rehydrating it by adding distilled water in a proportion equivalent to 1 mL per gram of dry mucilage [14]. This rehydration allowed the biopolymer to reactivate within the soil matrix, reproducing its natural gelatinous behaviour and promoting cohesion between particles.

3.3.3. Tara Gum

Tara gum is a natural galactomannan polysaccharide extracted from the endosperm of Caesalpinia spinosa seeds. Its structure consists of a main chain of mannose linked by β (1 to 4) bonds and lateral branches of galactose linked by α (1 to 6) bonds, with an approximate mannose: galactose ratio of 3:1, which gives it high viscosity and stability in aqueous solution. Composed mainly of polysaccharides (77%), accompanied by water and traces of proteins, it is used as a thickener, gelling agent, and stabiliser in the food, pharmaceutical, and cosmetic industries [39, 40]. Its colloidal structure gives it high water absorption capacity, cohesive properties, and the formation of dense, stable solutions, which promote apparent bonding between particles, as shown in Figure 8. These characteristics improve the mechanical strength and durability of granular and fine materials, as they increase cohesion and limit water erosion [15]. Table 3 presents the properties of chia mucilage.

Table 3. Properties of Chia Mucilage

Property	Value	Description
Carbohydrate composition	Galactomannans (77% polysaccharides)	Main mannose chain with galactose branches (M: G=3:1), responsible for its high viscosity [39].
Proteins and secondary compounds	Traces (low protein and phenolic fraction)	They contribute marginally to surface activity [39].
Polysaccharide structure	Neutral galactomannan	Its colloidal structure promotes the formation of dense solutions, useful as a thickener and cohesive agent in aqueous media [40].
Water absorption capacity	High	It hydrates and forms viscous solutions, increasing moisture retention and promoting cohesion among fine particles [40].
Viscosity of the extract	High (dependent on concentration and chemical modification)	The addition of acrylic monomers results in a marked increase in the viscosity of the solution [40].

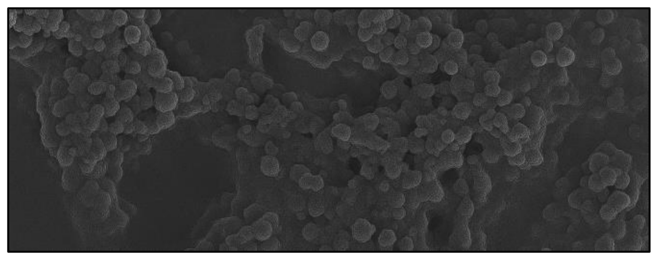

Fig. 8 Tara gum [15]

Based on a review of the literature, it was found that a study that applied an emulsion obtained from tara gum (Caesalpinia spinosa) reported an optimal dose of 0.3% relative to the dry weight of the soil in loess, achieving resistance to more than 30 hours of continuous precipitation with an erosion rate of only 2%, and 0.4% relative to the dry weight of the soil in lateritic soil, achieving a simple compressive strength of 3.7 MPa, approximately three times higher than the value of untreated soil [15]. Based on this reference value, in this research, tara gum will be applied in a range of 0.2%, 0.3%, 0.4%, 0.5%, and 0.6% by weight of dry soil in order to experimentally validate its effect on strength and reduction of susceptibility to liquefaction.

Obtaining Tara Gum

Tara gum was obtained from a commercial product in powder form [41], produced by mechanical processes of separation and grinding of the endosperm of the Caesalpinia spinosa seed. The procedure was developed with the aim of obtaining a homogeneous and fully hydrated biopolymer suitable for use in soil stabilisation. The procedure described in Figure 9 is divided into two parts: (a) the dosing of powdered products, in this case tara gum powder, which was weighed in precise quantities for each experimental mixture to ensure the correct gum-to-water ratio, and (b) the preparation of the viscous solution, which at a proportion of 1:100 (w/v) consisted of tara gum powder and distilled water. This solution was continuously stirred for 2 hours at 70 °C to ensure complete hydration and dissolution of the galactomannan. It was then allowed to cool to room temperature and prepared for application in the soil mixtures. This procedure facilitated the homogeneous distribution of the biopolymer, its assimilation within the granular matrix, and its encapsulation during the stabilisation tests.

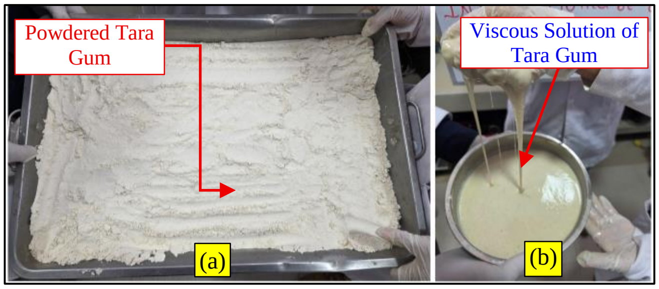

Fig. 9 Tara Gum

3.4. Soil Sampling

The soil samples used in this study were provided by the C3 Ingenieros laboratory, where drilling and sampling were conducted using the Standard Penetration Test (SPT) as an in situ characterisation technique [42, 43]. This enabled the extraction of representative samples from the target strata for the associated geotechnical study. The samples, recovered with the split sampler, were used for visual description and classification according to the SUCS system, as well as to determine the natural moisture content and Atterberg limits in those strata with fine fractions. In this way, basic geotechnical characterisation information was obtained to complement the strength parameters determined in the field based on the number of blows of the SPT.

During the exploration campaign, the laboratory reported that the boreholes reached a depth of 10 m, with the SPT being applied at regular intervals of 1.5 m. In the process, the presence of the water table was identified at a depth of approximately 4 m below the natural ground level. The field blow values (N) provided represent the dynamic resistance of the ground, while the N_{60} values correspond to the correction of these blows to a standard efficiency of 60%. Subsequently, the overload correction factor (C_n) was applied, which adjusts the resistance according to the effective vertical pressure, obtaining the corrected indices $(N_1)_{60} = N_{60} \cdot C_n$ [44, 45]. Table 4 shows the results obtained in the test.

Table 4. SPT test

Z (m)	N (blows)	N_{60}	$(N_1)_{60}$
1.50	10.00	6.00	7.80
3.00	12.00	7.20	9.36
5.00	15.00	9.00	11.70
7.50	20.00	12.00	15.60
10.00	24.00	14.40	18.72

The values obtained from (N1)60 ranged from 7.8 to 18.72 in the first 10.0 m of depth, which, according to international criteria, corresponds to a deposit of loose to moderately dense sand [44, 45]. Under these conditions, and also considering the presence of a shallow water table, the soil evaluated showed high susceptibility to liquefaction in the event of moderate to strong earthquakes. From this point, samples located at a depth of 5 meters were taken as the study stratum, considering this to be the most representative and critical section of the profile. This intermediate state reflects greater susceptibility to the generation of pore pressures and loss of shear strength under seismic stresses, compared to the altered surface strata or the deeper, more densified strata. Likewise, the water table accentuates the potential for liquefaction in this horizon, making it the most suitable control point for the analysis and reproduction of field conditions in laboratory tests.

Fig. 10 Soil characterisation

3.4.1. Soil Characterisation

For soil characterization, the first step consisted of quartering the material, shown in Figure 10 (a), with the aim of obtaining a representative and homogeneous sample for laboratory testing.

Subsequently, the moisture content test was performed according to ASTM D2216 [46], illustrated in Figure 10 (b), and particle size analysis in accordance with ASTM D422-63 [47], by progressive sieving through standardized meshes, as shown in Figure 10 (c).

The findings indicate that the natural moisture content of the soil is 4.5%, which is typical of materials with normal water retention and moderate permeability. The soil is predominantly composed of sand (94.2%), with 2.8% gravel and 2.8% fines, suggesting a granular structure with low plasticity and cohesion. The particle size distribution curve exhibits a steep slope and a lack of intermediate fractions, which allowed it to be classified as poorly graded soil (SP) according to the USCS. These characteristics indicate an alluvial origin, associated with deposits of similarly sized particles, with a tendency towards low compaction and a high void ratio, as shown in Figure 11.

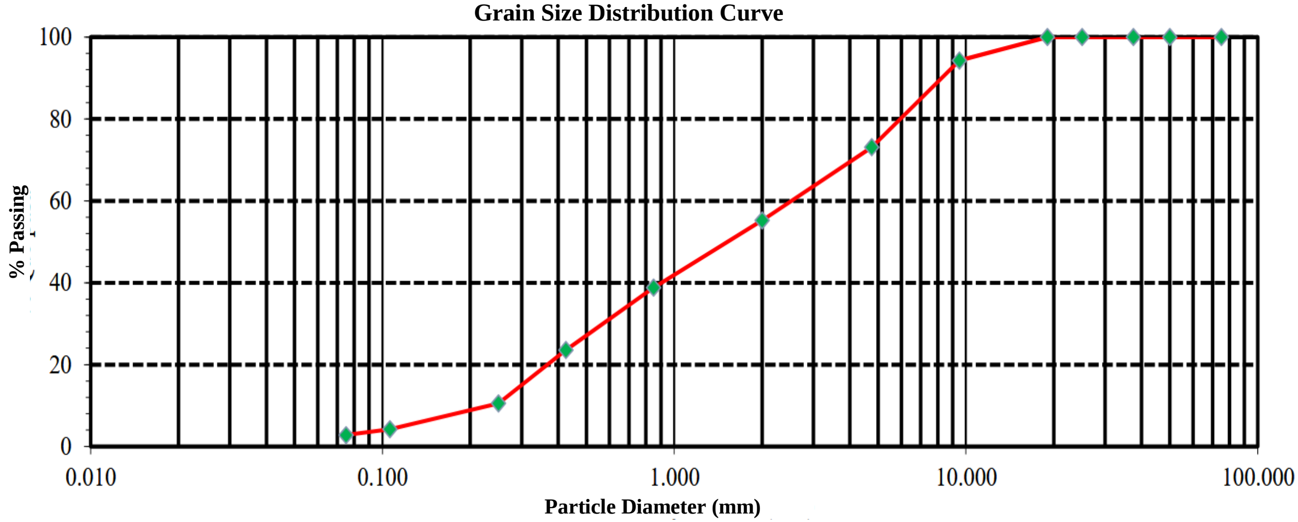

Fig. 11 Particle size distribution curve

In addition, Atterberg limits were determined in accordance with ASTM D4318 [48], with the sing material passing the No. 40 sieve. The results indicated a liquid limit of 0% and Non-Plastic (NP) behaviour, confirming the absence of active clay, which is consistent with granular soils exhibiting low cohesion and limited moisture retention. Based on these results, the material was classified according to geotechnical standards. Under the USCS, it was identified as SP (poorly graded sand with gravel), while under AASHTO, it corresponds to A-2-4(0). This classification indicates a sandy soil with low cohesion and plasticity, an unfavorable condition in the Pilcomayo area due to its higher susceptibility to liquefaction under saturation and seismic loading. Table 5 summarises the values obtained in the basic characterisation.

Table 5. Soil Characterisation

Property	In situ soil
Moisture Content (%)	4.5
Liquid Limit (LL%)	NP
Plastic Limit (LP%)	NP
Plasticity Index (PI%)	NP
SUCS classification	SP - poorly graded sand with gravel
AASHTO classification	A-2-4(0)

3.4.2. Specific Gravity ASTM D854

Specific gravity (Gs) is a fundamental geotechnical parameter defined as the ratio between the unit weight of soil solids and that of water at 4 °C. It provides an indirect indication of the mineral composition and intrinsic density of soil particles [49, 50].

It is commonly determined using the water pycnometer test established in ASTM D854 [51]. To do this, oven-dried and pulverized natural soil samples were placed in a calibrated volume pycnometer, to which distilled water was added until it was full, as shown in Figure 12 (a).

The assembly was then subjected to controlled agitation and air bubble removal to ensure volumetric accuracy, as shown in Figure 12 (b).

Finally, the weights corresponding to each stage of the test were recorded, and the value of Gs = 2.767 was calculated, which was adopted as a reference for the initial characterisation of the soil and for the design of the specimens treated with biopolymers.

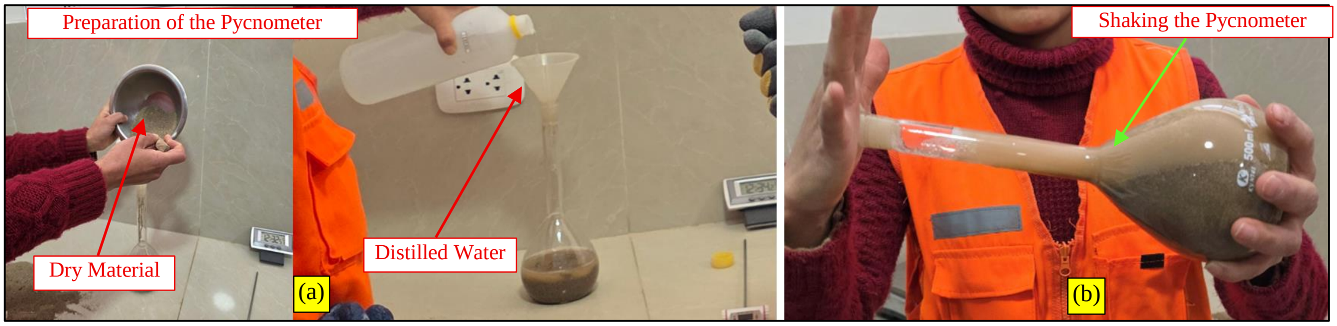

Fig. 12 Specific gravity ASTM D854

3.4.3. Standard Proctor

The standard Proctor test is a laboratory test widely used in geotechnical engineering to determine the compaction characteristics of soils and granular materials, in particular the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) [52, 53]. In accordance with ASTM D698 [54], The process was carried out in three main phases, as shown in Figure 13: (a) preparation of the material, where the previously dried and sieved sample was mixed with different amounts of distilled water, ensuring uniform distribution of moisture throughout the soil volume; (b) compaction by layers, carried out in a cylindrical mould of standard dimensions, by applying 25 blows per layer with a 2.5 kg hammer, falling from a height of 30.5 cm, developing a compaction energy of approximately 594 kJ/m³; and (c) levelling and removal of the mould, a stage in which excess material was removed and the upper surface was levelled to determine the wet weight and subsequently calculate the dry density of the specimen. As a result of the test, a maximum dry density of 1.681 g/cm³ and an optimum moisture content of 15.5% were obtained, values that were considered as a reference for the compaction and comparison processes in subsequent experimental treatments.

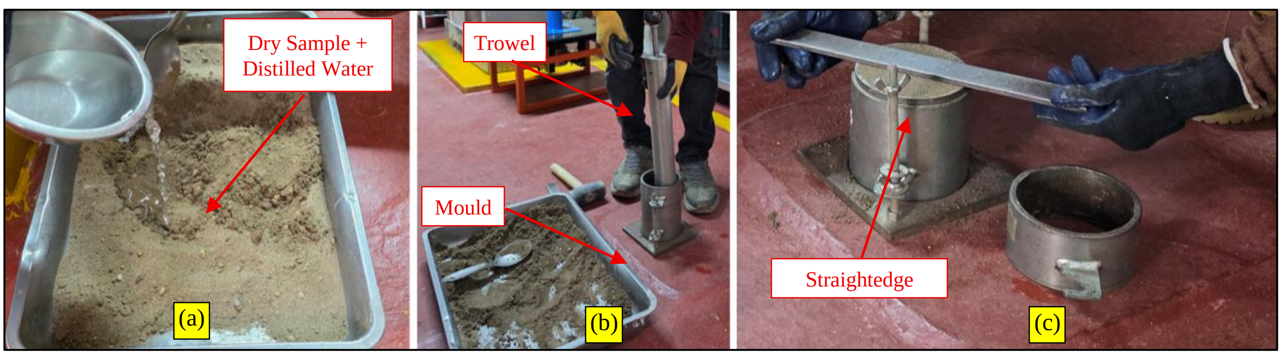

Fig. 13 Standard proctor

3.4.4. Maximum and Minimum Density of Granular Soils

The determination of maximum and minimum density of granular soils is one of the measurements carried out to establish limits in geotechnical engineering for a given level of compaction. These measurements of void ratios (emax) and (emin) are essential for determining relative density (Dr), which is a measure of the degree of compaction of the soil relative to its loosest and densest states [55, 56]. For this purpose, the two standardised techniques ASTM D4253 [58] and ASTM D4254 [58] are applied. These methods are commonly used to characterise sands and gravels for laboratory testing and for analysing the mechanical behaviour of materials under static and dynamic loading conditions.

ASTM D4253 Maximum Density Test

The maximum density test was performed in accordance with ASTM D4253, with the purpose of determining the minimum void ratio (emin) [57]. The test was divided into three phases, as shown in Figure 14: (a) the samples were completely oven-dried at 105 °C until a constant mass was achieved, ensuring that all moisture was removed; (b) filling of the calibrated cylindrical metal mould, with an internal diameter of 71 mm and a height of 146 mm, in successive layers without prior compaction or segregation, subsequently placing an overload disc that exerted a uniform pressure of approximately 14 kPa; and (c) vibration on a laboratory table for 8 minutes at a frequency close to 60 Hz until the height of the sample stabilised, indicating the condition of maximum densification. Once the process was complete, the disc was removed, the surface was leveled to the level of the mould, and the mass of the sample was recorded using a precision balance. As a result, a minimum void ratio of emin = 0.398 was obtained, which represents the densest state achievable by the soil under controlled vibration conditions.

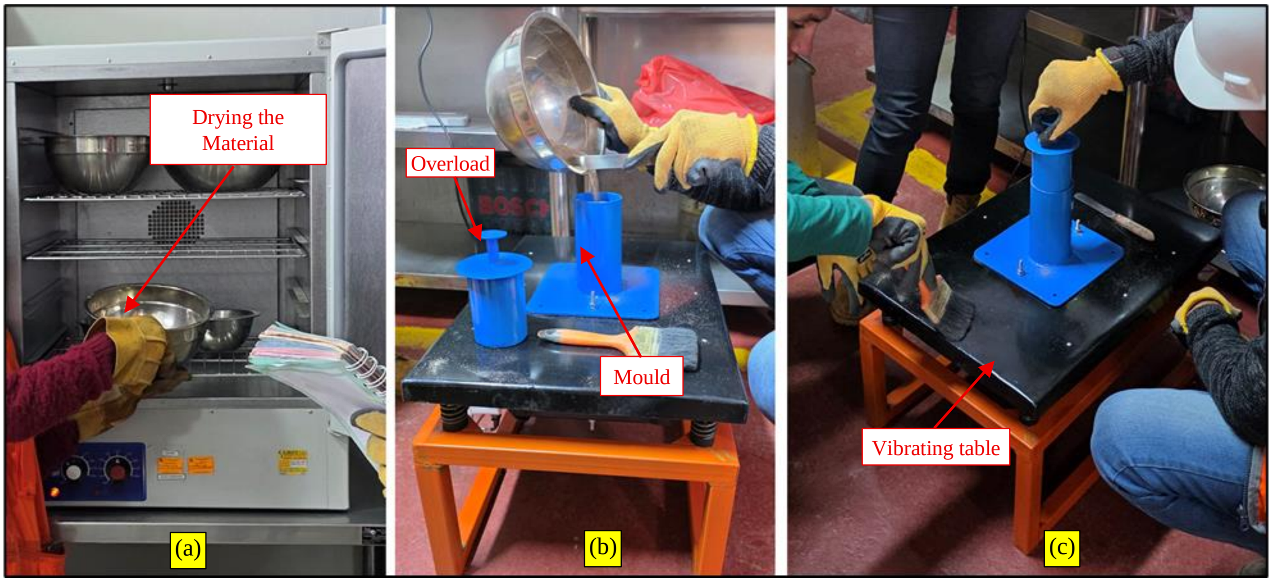

Fig. 14 ASTM D4253 test

ASTM D4254 Minimum Density Test

In addition, the minimum density test was carried out in accordance with ASTM D4254, with the aim of establishing the maximum void ratio (emax) [58]. The process was carried out in three main phases, as shown in Figure 15: (a) drying of the material in an oven at 105 °C until a constant mass was reached, ensuring complete removal of moisture; (b) filling of the calibrated cylindrical metal mould using a metal funnel located 25 mm above the upper edge of the mould, allowing the soil to be deposited by gravity in a single continuous operation, without applying compaction, vibration or tamping; and (c) levelling of the surface, carried out carefully with a metal ruler to remove excess material, taking care not to alter the loose structure obtained. Subsequently, the mass of the soil was recorded using a precision balance and, with the known volume of the mould, the corresponding density was determined. As a result, a maximum void ratio of emax = 0.718 was obtained, which represents the loosest achievable state of the soil. This parameter, together with the emin determined according to ASTM D4253, made it possible to define the compactness range of the material and establish the optimum relative density for the preparation of the reconstituted test specimens used in subsequent mechanical tests.

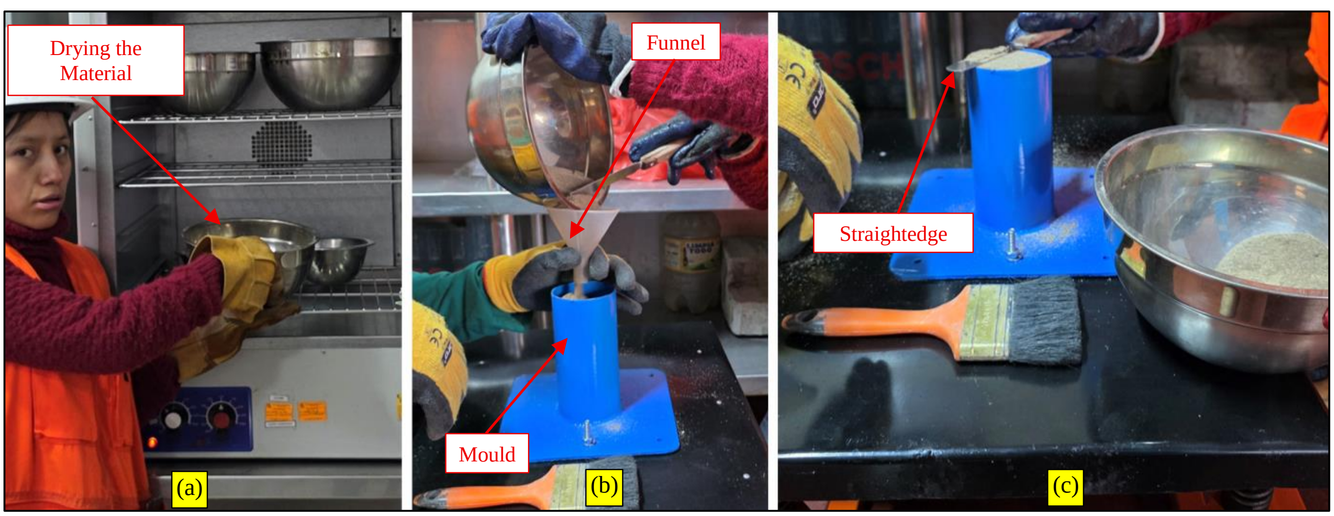

Fig. 15 ASTM D4254 test

3.4.5. Sample Reconstruction

The sample obtained by the SPT showed a significant level of alteration due to the drilling process and the use of the split sampler, which caused loss of natural structure, variation in the degree of compaction, and disturbances in moisture content [59]. Consequently, it was not possible to use it directly in the triaxial test, as it did not reliably represent the in situ conditions of the soil. For this reason, it was decided to use the recovered material solely as a basis for the reconstruction of test specimens. There are various methods of reconstructing test specimens used in triaxial tests, such as layered compaction, wet tamping, wet deposition, and dry pluvial, each with advantages and limitations associated with the type of soil and the condition to be represented [60, 61]. In this context, it was necessary to define control parameters that would ensure that the reconstructed specimens adequately represented the natural state of the soil. To this end, relative density became a fundamental criterion, as it allows the preparation of laboratory samples to be linked to the results obtained in the field. This value was estimated from the maximum (emax) and minimum (emin) void ratios, calculated according to standardised norms and relationships reported in previous research [62]. First, the coefficient Cd (Equation 1), which depends on the particle size distribution and the fines content, was determined using the expression:

$$Cd = \frac{9}{(emax - emin)^{1.7}} \quad (1)$$

Subsequently, the relative density was calculated from the corrected number of blows from the SPT test $(N1)60$, applying the following relationship (Equation 2):

$$Dr = \sqrt{\frac{(N_1)_{60}}{Cd}} \quad (2)$$

Based on this relative density value, the void ratio (e) was calculated using Equation 3.

$$e = emax - \frac{Dr}{100}\,(emax - emin) \quad (3)$$

With this void ratio, the target dry density was determined from the expression (Equation 4), the density of water ρw=1.0 g/cm^3:

$$\rho d = \frac{Gs * pw}{1+e} \quad (4)$$

Finally, the dry mass value required to compact the test specimens based on their volume (70 mm x 140 mm) was obtained using Equation 5. Table 6 shows the results obtained until the mass used in the test specimens was reached:

$$md = \rho d * V \quad (5)$$

Table 2. Relative soil density

Description	Value
emax	0.718
emin	0.398
Cd	62.44
Dr	0.433
Dr (%)	43.286
e	0.579
ρd (g/cm^3)	1.752
Volume (cm^3)	538.783
md (kg)	0.944

Equation 6 is used to calculate the water required for each test tube. From this, the data for the corresponding additives and tests are obtained, as shown in Table 7.

$$mw = OCH * md \quad (6)$$

Table 7. Quantity of Liquids for Specimens

Description	Dosage (%)	Amount of biopolymer (ml)	Water (ml)
Natural soil	15.5%	0.000	146.298
Nopal Mucilage	4%	37.754	108.544
	6%	56.632	89.667
	8%	75.509	70.790
	10%	94.386	51.912
	12%	113.263	33.035
Chia Mucilage	1%	9.439	136.860
	1.5%	14.158	132.140
	2%	18.877	127.421
	2.5%	23.597	122.702
	3%	28.316	117.983
Tara Gum	0.2%	1.888	144.411
	0.3%	2.832	143.467
	0.4%	3.775	142.523
	0.5%	4.719	141.579
	0.6%	5.663	140.635

Wet Tamp Method

The wet tamp method is a test specimen reconstruction technique widely used in granular and mixed soils, which consists of compacting the previously moistened material in successive layers inside a cylindrical mould. This preparation method allows specimens with controlled densities and moisture conditions to be obtained, ensuring internal homogeneity and repeatability of results in subsequent tests. Its application is particularly useful in studies of soils treated with additives or biopolymers, as it facilitates adequate distribution of the stabilising agent in the soil matrix and ensures the structural integrity of the test specimen during handling and testing [16, 60, 63].

Wet Tamping Procedure [16]

First, the material was dried in an electric convection oven at 105 °C for a period of 24 hours, until it reached a constant mass. Subsequently, the natural soil sample was cooled to room temperature and moistened with distilled water until it reached a moisture content close to the Optimum Compaction Moisture (OCM) obtained in the standard Proctor test. Water was added gradually, and the mixture was homogenised manually in stainless steel trays, ensuring uniform distribution of moisture throughout the soil mass. Unlike a conventional procedure based on Proctor's Maximum Dry Density (MDD), this study adopted the void ratio (e) as a control criterion, determined from the values of emax, emin, and the target relative density Dr, shown in Table 6. This approach was considered more representative of natural soil conditions, as it directly reflects the packing state of the particles and their relationship to in situ behaviour.

In the case of mixtures with additives, the water needed to achieve the OMC was incorporated in the form of pre-prepared biopolymer solutions by dissolving the additives in distilled water as appropriate, so that the compaction moisture was not provided by water alone, but by these viscous solutions. Based on the reference OMC, specific dosage ranges were established for each additive: tara gum, chia mucilage, and nopal mucilage, as shown in Table 7. These dosages were selected in order to experimentally validate the effect of each biopolymer on soil strength and the reduction of its susceptibility to liquefaction. This process can be seen in Figure 16: (a) standard mixture with distilled water; (b) incorporation of nopal mucilage; (c) incorporation of chia mucilage; and (d) incorporation of tara gum.

Fig. 16 Mixtures of natural additives + soil with Dr and OCH

The wet mixtures were placed in calibrated cylindrical metal moulds measuring 70 mm in diameter and 140 mm in height to prepare test specimens for consolidated undrained triaxial tests (CU, static and cyclic). Each test specimen was formed by layering the material into five 4 cm-thick strata. Each layer was compacted manually with a flat-faced cylindrical metal rammer, applying 25 uniform blows until the corresponding height was reached. To ensure adhesion between layers and prevent the formation of planes of weakness, before placing each new fraction, the previously compacted layer was scratched superficially by approximately 0.1 mm with a metal spatula. Once formed, the specimens were immediately removed from the mould and placed on trays under controlled laboratory conditions, where they were kept for 28 days at 22 °C and exposed to ambient air, in order to allow the formation and stabilisation of the hydrogel network generated by the biopolymers. This air-curing procedure, recommended in previous research on biopolymer-stabilized soils, preserves the integrity of the gel and ensures representative behaviour in mechanical tests [16]. Figure 17 shows the final stage of the procedure described for wet tamping.

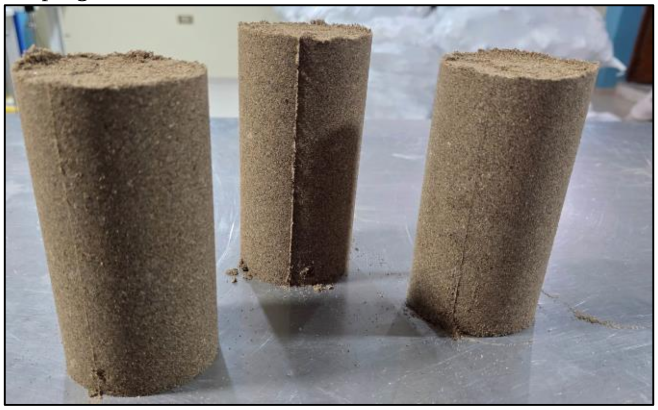

Fig. 17 Final specimens made by wet tamping

3.4.6. Static CU Triaxial Test

The Consolidated Undrained (CU) triaxial test, regulated by ASTM D4767 [64], is a laboratory procedure designed to determine the total and effective shear strength parameters of cohesive soils under conditions of prior consolidation and undrained loading. In this test, the soil sample is first saturated and consolidated under controlled confining pressure, then subjected to a static monotonic axial load while pore pressures and deformations are recorded.

The total strength parameters correspond to those obtained considering the stresses without discounting the pore pressure (c and φ), and reflect the immediate response of the soil under undrained conditions. In contrast, the effective strength parameters (c' and φ') are calculated taking into account only the effective stresses, i.e., the difference between the total stress applied and the pore pressure, which allows the actual behaviour of the soil's solid skeleton to be evaluated. In this way, it is possible to characterise cohesion and friction angle in both total and effective terms, and to comprehensively evaluate the response of the soil to static and dynamic stresses [65, 66].

Static Triaxial CU Test Procedure

The experimental process was carried out in four main phases, shown in Figure 18: (a) placement of the latex membrane, carefully adjusted over the surface of the test specimen using the vacuum device, avoiding the formation of bubbles; (b) placement of filter paper on both bases to ensure uniform drainage during consolidation and cutting; (c) installation of porous stones, which ensured adequate pressure transmission and an efficient connection between the sample and the measurement system; and (d) assembly of the unit in the triaxial cell, connected to the cell pressure, pore pressure and automated controller units.

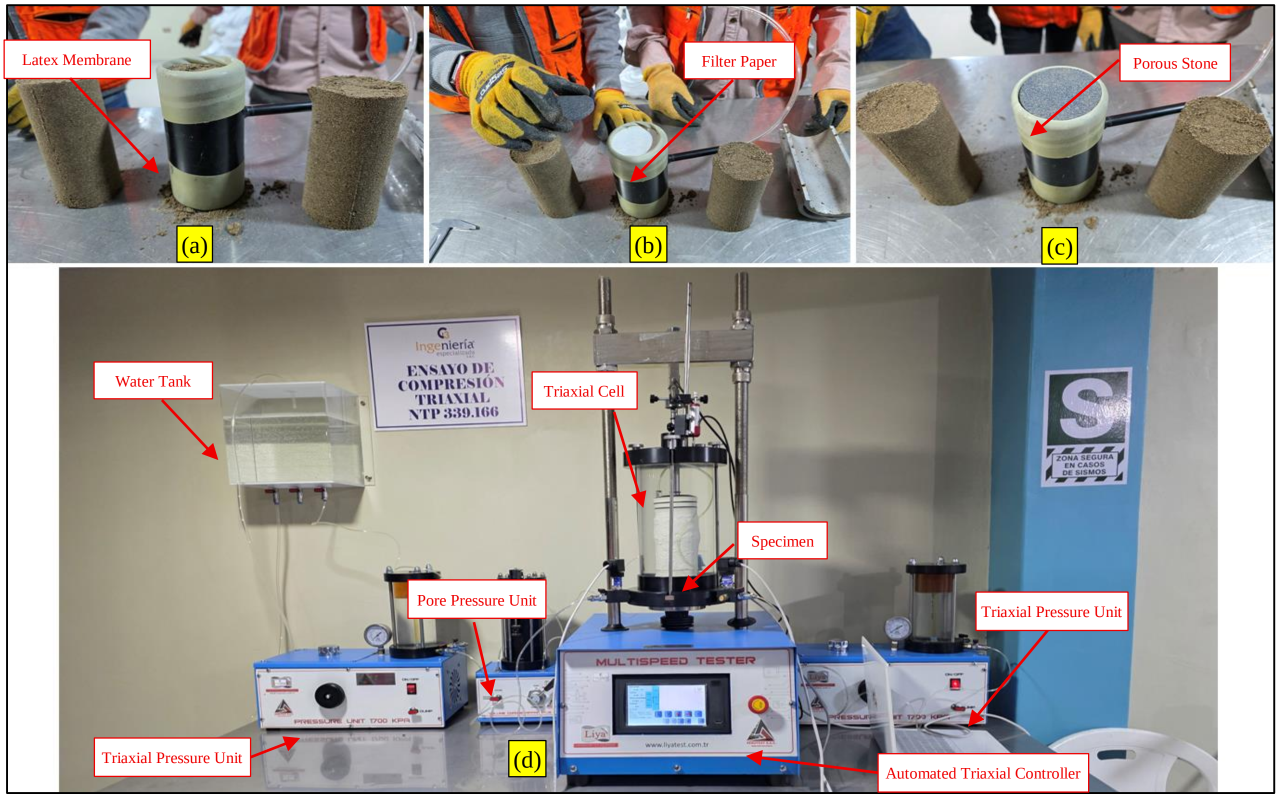

Fig. 18 Static CU Triaxial test

The specimens used had a diameter of 70 mm and a height of 140 mm. The samples were then placed on the pedestal of the triaxial apparatus. The saturation process was completed in three stages: first, air was displaced by injecting CO_2 gas into the pores of the specimen; subsequently, a volume of water equivalent to twice the specimen volume was circulated under vacuum (i.e., deaired). Afterward, back pressure was gradually applied to ensure full saturation, using Skempton's B coefficient as a reference, with B > 0.95 considered satisfactory. The specimens were then isotropically consolidated under effective confining pressures of 2, 4, and 6 kg/cm², with drainage valves kept open during consolidation until volumetric and pore pressure equilibrium was achieved. At this stage, undrained shearing (static CU) was performed by applying a strain-controlled axial load at a constant rate of 1% axial strain per minute. Axial load, vertical displacement, cell pressure, and pore pressure were recorded. Each specimen was tested until failure, defined by the attainment of peak strength.

3.4.7. Cyclic CU Triaxial Test ASTM D5311

The focus of this section is to analyze the nature of Cyclic Triaxial (CT) test procedures applied to saturated soils subjected to dynamic loading (simulating earthquakes/waves), as specified in ASTM D5311 [67]. This is a laboratory test used to determine the response of saturated soils to repeated dynamic loading, including seismic or wave-induced actions. In this test, cylindrical soil specimens are fully saturated and consolidated under a controlled confining pressure, and then subjected to cyclic sinusoidal axial loading under either drained or undrained conditions. During testing, strain, pore water pressure, and stress levels are continuously monitored. This enables the relationship between Cyclic Shear Stress (CSR), the Number of Cycles to Liquefaction (NL), and the development of deformations to be established, as well as the assessment of liquefaction resistance and soil stiffness degradation [68, 69]. In pore pressure analysis, the parameter $\Delta u/\sigma'_3$, evaluated at the peak of cyclic loading, is essential for estimating liquefaction susceptibility [16, 70]. The values of r_u are presented in Table 8.

Table 8. Criteria for r_u pico [16, 70]

r_u peak	Susceptibility
≥ 0.95	High (liquid)
0.80-0.95	Moderate
< 0.80	Low (non-liquefiable)

The accredited laboratory performed CU cyclic triaxial tests following international protocols for soils susceptible to liquefaction, ensuring complete saturation of the test specimens, isotropic consolidation under representative effective stress, and controlled application of dynamic loads. To this end, saturation levels were verified using Skempton's B coefficient (B ≥ 0.95), and an effective confining pressure of 100 kPa was adopted, a value selected for its correspondence with the in situ stress state of the critical layer of Pilcomayo, located at a depth of 5 m and subjected to saturated conditions. The dynamic stresses were applied using 1 Hz sinusoidal waves, using cyclic stress ratios (CSR = 0.15, 0.20, and 0.25) defined according to the expected seismic severity: the first two levels to simulate moderate to strong demands, and a CSR of 0.25 to represent an extreme scenario equivalent to an earthquake of magnitude Mw 7.5, a criterion widely validated in liquefaction studies [16]. During the cycles, axial deformation, pore pressure, and stress response were recorded, defining the liquefaction state when the double amplitude axial deformation reached 5% and complementing it with the peak ru parameter. With the records obtained, the laboratory generated the pore pressure evolution and cumulative deformation curves, as well as the CSR-NL relationships that allow the liquefaction resistance of the material to be evaluated.

4. Results

4.1. CU Triaxial Test

The results obtained in the static Consolidated Undrained (CU) Triaxial Test are presented below, which evaluated the shear strength parameters of natural soil and mixtures treated with biopolymers. This procedure made it possible to determine the total and effective cohesion values, as well as the corresponding friction angles, in order to analyze the effect of different dosages of nopal mucilage, chia mucilage, and tara gum on the mechanical behaviour of the soil.

4.1.1. Effective and Total Cohesion

Table 9 presents the values of total and effective cohesion obtained from the CU triaxial test. The natural soil exhibits zero cohesion (0.00 kg/cm²), confirming its granular behaviour without cohesive fines. With the incorporation of nopal mucilage, cohesion increases progressively, reaching values of 1.19/0.92 kg/cm² (4%), 1.72/1.36 kg/cm² (6%), 2.01/1.63 kg/cm² (8%), and a maximum of 2.14/1.78 kg/cm² (10%). This increase is attributed to the formation of colloidal bridges that enhance interparticle contact. However, at 12%, a reduction in cohesion to 1.84/1.49 kg/cm² is observed, indicating biopolymer oversaturation and the development of a softer soil matrix.

The cohesion values for chia mucilage showed an increase from 0.98/0.79 kg/cm² at 1% to 1.64/1.31 kg/cm² at 2%, followed by a decrease to 1.55/1.24 kg/cm² at 2.5% and 1.47/1.18 kg/cm² at 3%. This behaviour is attributed to increased dosages that eventually produced a lubricating rather than cohesive effect, reducing stress transfer between particles. Finally, tara gum exhibited the highest values, with an initial cohesion of 1.69/1.38 kg/cm² at 0.2%, increasing to 1.97/1.61 kg/cm² at 0.3%, and reaching 2.49/2.07 kg/cm² at 0.4%. This is attributed to the tendency for cross-linking and the formation of strong gel structures that enhance soil cohesion. Subsequently, at 0.5% and 0.6%, the values decreased slightly to 2.36/1.94 kg/cm² and 2.27/1.88 kg/cm², respectively, showing that higher doses did not provide greater benefits. Overall, the results in the table showed that the three biopolymers modified the soil microstructure by generating additional bonds and retaining moisture, but each had an optimal dosage range where maximum efficacy was achieved.

Table 9. Effective and Total Cohesion

Description	Dosage (%)	Total cohesion (kg/cm²)	Effective cohesion (kg/cm²)
Natural soil	0.0%	0.00	0.00
Nopal Mucilage	4%	1.19	0.92
	6%	1.72	1.36
	8%	2.01	1.63
	10%	2.14	1.78
	12%	1.84	1.49
Chia Mucilage	1%	0.98	0.79
	1.5%	1.27	1.02
	2%	1.64	1.31
	2.5%	1.55	1.24
	3%	1.47	1.18
Tara Gum	0.2%	1.69	1.38
	0.3%	1.97	1.61
	0.4%	2.49	2.07
	0.5%	2.36	1.94
	0.6%	2.27	1.88

Figure 19 shows the increase in total and effective soil cohesion when biopolymers are incorporated, compared to natural soil, which showed no cohesion. With nopal mucilage, the 10% dose reached 2.14 kg/cm² of total cohesion and 1.78 kg/cm² of effective cohesion, which were 10.7 and 8.9 times more than natural soil, respectively. Subsequently, at 12%, the values decreased to 1.84 kg/cm² and 1.49 kg/cm², which meant a reduction of 14% and 16% from the maximum reached.

In the case of chia mucilage, maximum effectiveness was obtained at 2%, with 1.64 kg/cm² and 1.31 kg/cm², equivalent to 8.9 and 7.2 times the natural soil, but when increased to 3%, the values dropped to 1.47 kg/cm² and 1.18 kg/cm², a reduction of 10% and 9% from the peak reached.

Finally, tara gum showed the best performance, reaching 0.4% 2.49 kg/cm² of total cohesion and 2.07 kg/cm² of effective cohesion, which represented 13.2 and 11.5 times the value of the untreated material. At higher doses, a slight decrease was observed: at 0.6%, the values were 2.27 kg/cm² and 1.88 kg/cm², representing a decrease of 9% and 10% from the maximum. Overall, the graphs confirmed that the three biopolymers significantly increased cohesion in relation to natural soil, with tara being the most efficient additive, followed by nopal and, to a lesser extent, chia.

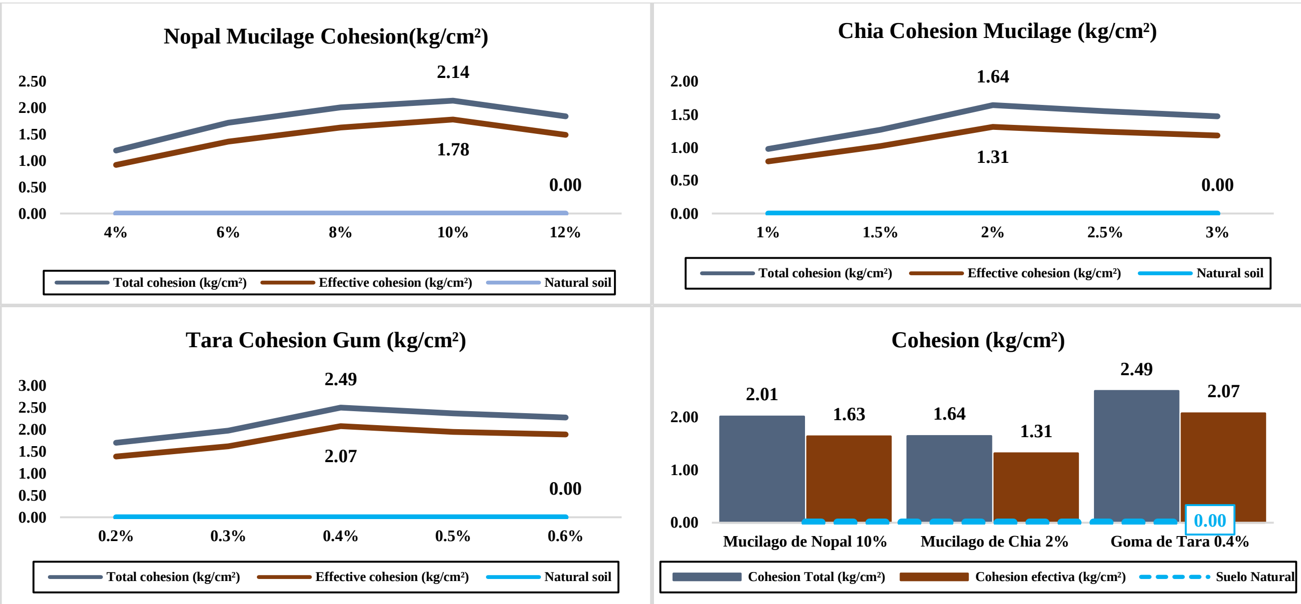

Fig. 19 Effective and Total Cohesion

4.1.2. Effective and Total Friction Angle

Table 10 shows the total and effective friction angle values obtained in the CU triaxial test. The natural soil recorded 34.14° of total friction and 35.83° of effective friction, values that reflected its characteristic behaviour without the presence of biopolymers. With the incorporation of nopal mucilage, the values showed a progressive reduction: at a dose of 4%, they reached 33.41° and 35.62°, at 6%, 32.97° and 35.11°, at 8%, 32.39° and 34.57°, reaching 32.06° and 34.26° at 10%, and finally decreasing to 31.79° and 33.88° at 12%. This decrease was explained by the lubricating effect of the mucilage, which, by coating the particles, reduced intergranular friction, although it maintained a slight contribution to effective resistance thanks to the colloidal bonds formed. In the case of chia mucilage, similar behaviour was observed: at 1%, the values were 33.82° and 35.41°, decreasing progressively to 32.76° and 34.32% at 3%, confirming that the mucilage created a softer environment that reduced the friction angle, although at moderate doses, a balance was maintained due to the viscosity of the biopolymer. Finally, tara gum showed a comparable pattern: it started at 33.71° and 35.38° at 0.2%, reached 33.29° and 34.86° at 0.3%, and gradually decreased to 32.51° and 34.05° at 0.6%, indicating that, although tara strengthened soil cohesion, it also decreased friction values due to the reduction of direct contact between particles.

Table 10. Effective and Total Friction Angle

Description	Dosage (%)	Friction Angle Total (°)	Friction Angle Effective (°)
Natural soil	0.0%	34.14	35.83
Nopal Mucilage	4%	33.41	35.62
	6%	32.97	35.11
	8%	32.39	34.57
	10%	32.06	34.26
	12%	31.79	33.88
Chia Mucilage	1%	33.82	35.41
	1.5%	33.47	35.02
	2%	33.11	34.68
	2.5%	32.92	34.44
	3%	32.76	34.32
Tara Gum	0.2%	33.71	35.38
	0.3%	33.29	34.86
	0.4%	32.81	34.37
	0.5%	32.66	34.21
	0.6%	32.51	34.05

Figure 20 shows the variations in the friction angle compared to natural soil, which allowed the relative decreases to be quantified. In nopal mucilage, the 10% dose showed a reduction in the total angle of 2.08°, equivalent to 6% less than the natural angle, while the effective angle was reduced by 1.57° (4.4% less). In chia, the behaviour was similar: at 2%, the total angle decreased by 1.03° (3% less) and the effective angle by 1.15° (3.2% less) compared to the natural angle, confirming a more moderate lubrication effect. Tara gum showed the most marked decreases: at 0.4%, the total angle decreased by 1.33° (3.9% less) and the effective angle by 1.46° (4.1% less). The overall comparison showed that, although all biopolymers reduced the angle of friction with respect to natural soil, the magnitude of the decrease was relatively low, always remaining within an acceptable range of variation. These results showed that the incorporation of biopolymers mainly modified the cohesion of the soil, while the angle of friction was affected to a lesser extent, maintaining the friction resistance capacity at values close to those of the natural material.

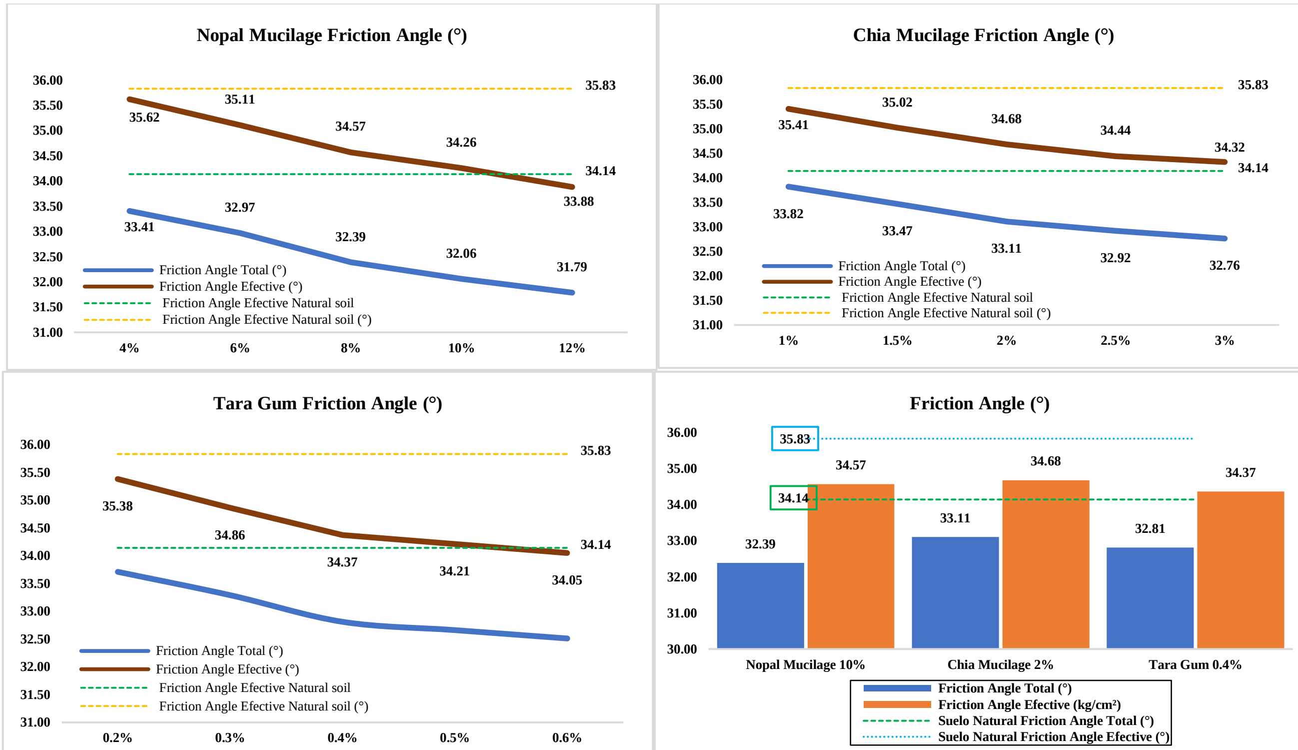

Fig. 20 Effective and Total Friction Angle

4.1.3. Admissible Capacity

Table 11 shows the permissible capacity values of natural soil and mixtures stabilised with biopolymers. Natural soil recorded a value of 1.24 kg/cm², corresponding to its untreated condition. With the addition of nopal mucilage, a progressive increase in strength was observed, reaching 1.57 kg/cm² at 4%, 1.71 kg/cm² at 6%, and a maximum of 1.82 kg/cm² at 8%, due to improved cohesion and rigidity. However, at 10% and 12%, the values decreased to 1.51 and 1.43 kg/cm², indicating that excess biopolymer reduced resistance. Chia mucilage showed a similar trend, reaching 1.58 and 1.67 kg/cm² at 1% and 1.5%, with a peak of 1.77 kg/cm² at 2%, followed by a decrease at higher dosages due to a lubricating effect. Tara gum proved to be the most effective additive, increasing from 1.38 kg/cm² at 0.2% to a maximum of 2.07 kg/cm² at 0.4%. Although values slightly decreased at higher contents, they remained above the natural soil. Overall, all biopolymers improved the allowable capacity, with optimal dosages of 8% for nopal, 2% for chia, and 0.4% for tara, the latter being the most efficient.

Table 3. Permissible Capacity

Description	Dosage (%)	qadm (kg/cm²)
Natural soil	0.0%	1.24
Nopal Mucilage	4%	1.57
	6%	1.71
	8%	1.82
	10%	1.51
	12%	1.43
Chia Mucilage	1%	1.58
	1.5%	1.67
	2%	1.77
	2.5%	1.54
	3%	1.49
Tara Gum	0.2%	1.38
	0.3%	1.63
	0.4%	2.07
	0.5%	1.96
	0.6%	1.88

Figure 21 compares the permissible capacity values with respect to natural soil (1.24 kg/cm²), which allowed the increases achieved with each biopolymer to be quantified. At 8%, nopal mucilage reached a value of 1.82 kg/cm², equivalent to 1.47 times that of natural soil, while at 12% it decreased to 1.43 kg/cm², remaining at 1.15 times the initial value. Chia mucilage performed best at 2%, with 1.77 kg/cm², which was 1.43 times that of the soil without an additive; however, at 3%, the value dropped to 1.49 kg/cm², equivalent to 1.20 times that of the natural soil. Tara gum achieved the highest increase: at 0.4%, it reached 2.07 kg/cm², i.e. 1.67 times more than the natural soil; even at 0.6%, it maintained 1.88 kg/cm², with an increase of 1.52 times. The overall comparison showed that the three biopolymers were effective in improving the bearing capacity compared to the natural soil, but tara stood out as the additive with the greatest reinforcement, followed by nopal and finally chia.

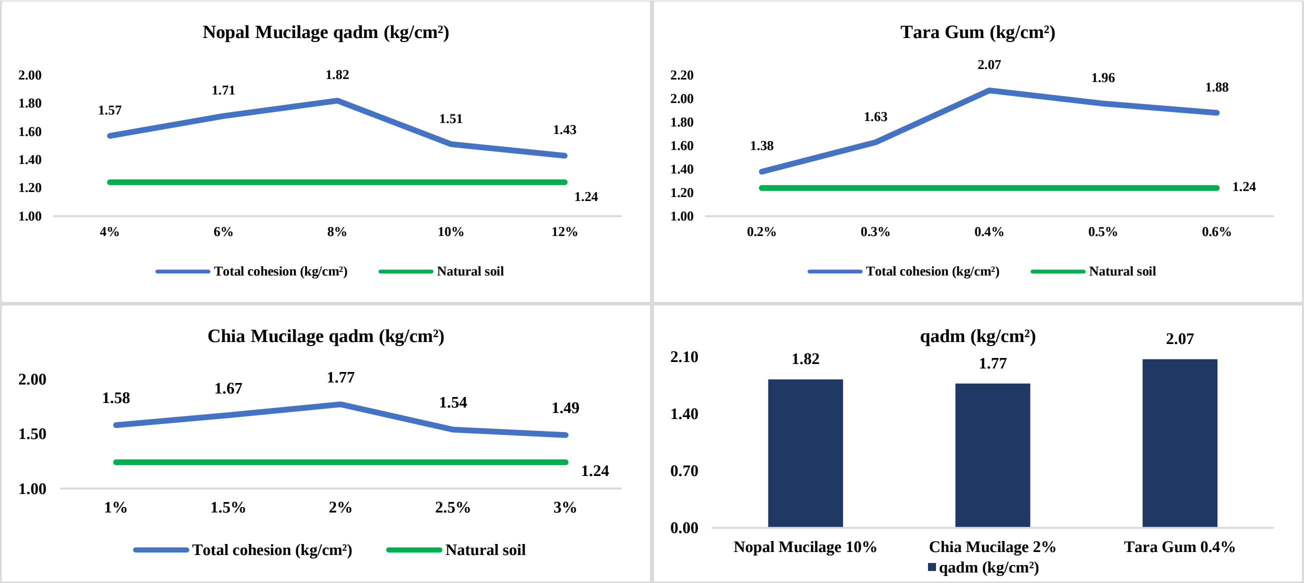

Fig. 21 Admissible Capacity

4.2. Cyclic Triaxial Test

The results obtained in the cyclic Consolidated Undrained (CU) Triaxial test are presented below. This test allowed the evaluation of the liquefaction resistance of natural soil and mixtures stabilised with biopolymers under repetitive dynamic loads. This procedure was used to analyse key parameters such as the number of cycles to liquefaction (NL) and the maximum pore pressure coefficient (ru peak), in order to classify the soil's susceptibility to liquefaction and determine the influence of different dosages of nopal mucilage, chia mucilage, and tara gum on improving its dynamic behaviour.

4.2.1. Resistance to Liquefaction

The results obtained are shown in Table 12. It was observed that the natural soil without the addition of biopolymers presented very low resistance to liquefaction, registering NL values of 15.4, 8.3, and 4.7 cycles for CSR of 0.15, 0.20, and 0.25, respectively. In contrast, the incorporation of biopolymers significantly increased the number of cycles required to achieve liquefaction. In the case of nopal, there was a progressive increase in NL from 74 cycles with 4% addition to a maximum of 101 cycles with 10%, decreasing slightly to 12%, which indicated the existence of an optimal dosage. Chia gum produced moderate improvements, reaching its highest efficacy with a 2% addition (NL=74, 40, and 23), after which the values began to decrease, suggesting that high doses generated an excess of mucilage with lubricating effects on the soil matrix. Tara gum yielded the best results, reaching NL values of 152, 82, and 46 cycles with 0.3%, and maximum values of 170, 91, and 52 cycles with 0.4%, far surpassing the other additives.

However, when the dosage was increased to 0.5% and 0.6%, the resistance decreased, showing that an excess of biopolymer reduced the effectiveness of the reinforcement. In all cases, it was confirmed that as the CSR increased, the number of cycles to liquefaction decreased, although the treated specimens always performed better than the natural soil. In summary, the biopolymers evaluated reduced susceptibility to liquefaction, with tara at low doses standing out as the most efficient additive, followed by nopal and finally chia with a more moderate effect.

Table 12. Number of Cycles

Description / Dosage	**CSR=0.15 → NL**	**CSR=0.20 → NL**	**CSR=0.25 → NL**	**Susceptibility**
	0.15	**0.2**	**0.25**	
Natural soil 0%	15.4	8.3	4.7	High
Nopal Mucilage 4%	74	40	22	Moderate
Nopal Mucilage 6%	85	45	26	Moderate
Nopal Mucilage 8%	97	52	30	Moderate
Nopal Mucilage 10%	**101**	**55**	**31**	Low
Nopal Mucilage12%	94	50	29	Moderate
Chia mucilage 1%	53	29	16	Moderate

Chia mucilage 1.5%	62	33	19	Moderate
Chia mucilage 2%	**74**	**40**	**23**	Low
Chia mucilage 2.5%	70	38	21	Moderate
Chia mucilage 3%	67	36	20	Moderate
Tara Gum 0.2%	80	43	24	Moderate
Tara Gum 0.3%	152	82	46	Moderate
Tara Gum 0.4%	**170**	**91**	**52**	Low
Tara Gum 0.5%	131	70	40	Moderate
Tara Gum 0.6%	104	56	32	Moderate

Figure 22 presents the results under three CSR conditions, showing significant improvements in the liquefaction resistance of soils stabilised with biopolymers. At a CSR of 0.15, the natural soil reached 15.4 cycles, while Nopal (10%) achieved 101 cycles, Chia (2%) 74 cycles, and Tara (0.4%) 170 cycles, representing increases of 6.6, 4.8, and 11 times, respectively. At a CSR of 0.20, the natural soil recorded 8.3 cycles, compared to 55 cycles for nopal, 40 for chia, and 91 for tara, maintaining similar improvement ratios. Under the most demanding condition (CSR = 0.25), the natural soil reached 4.7 cycles, while nopal, chia, and tara achieved 31, 23, and 52 cycles, respectively, again showing increases between 4.9 and 11 times. Overall, the results confirmed that the three biopolymers significantly reduced susceptibility to liquefaction under all conditions, highlighting tara as the most efficient additive in low doses, followed by nopal in intermediate concentrations and chia with a more moderate but consistent effect.

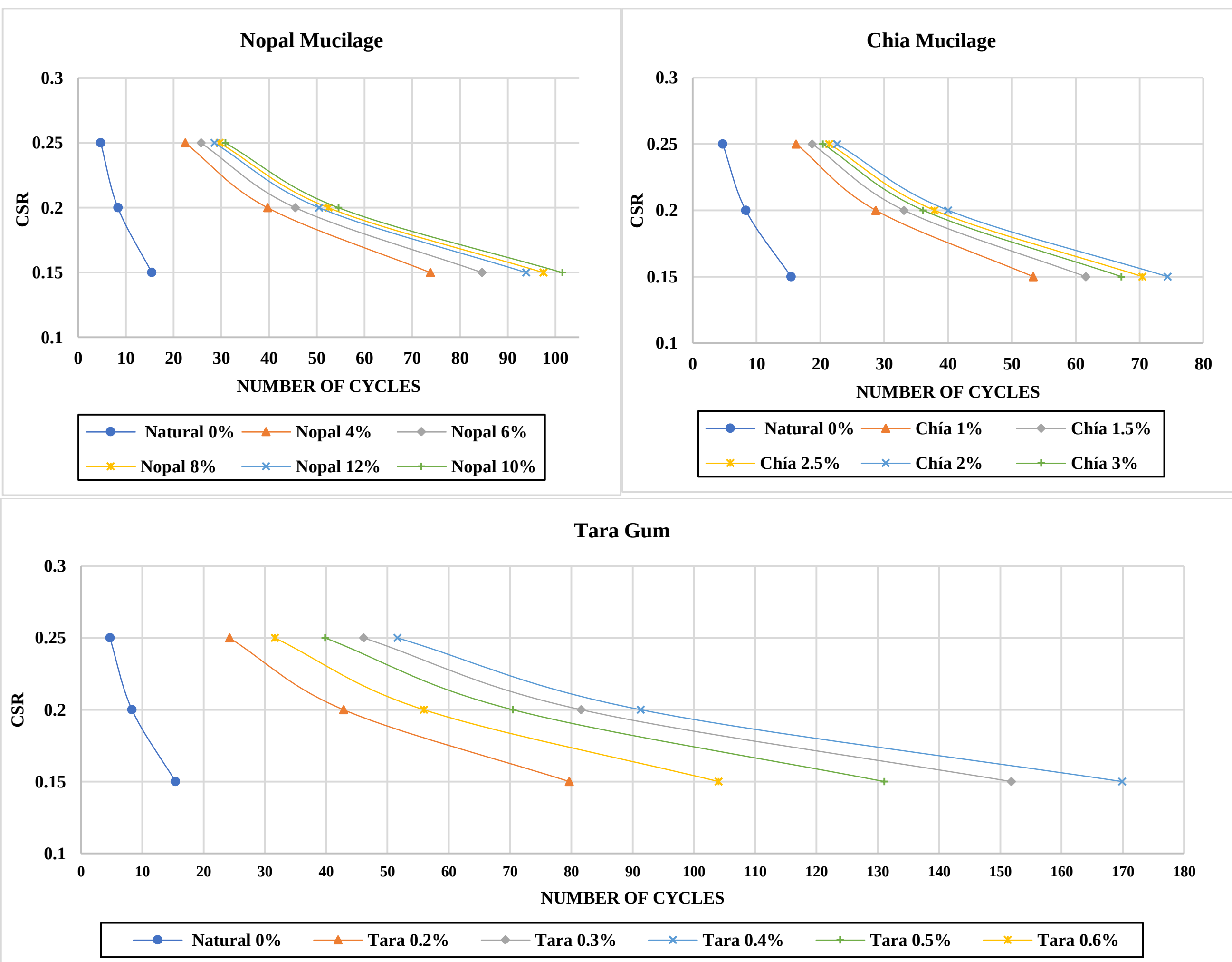

Fig. 22 Number of CSR Cycles

Table 13 shows the values for the number of cycles to liquefaction (NL), peak ru, and susceptibility classification. The natural soil reached a peak ru of 0.98, considered in the high susceptibility category, which explained why liquefaction occurred with only 15.4, 8.3, and 4.7 cycles for CSR of 0.15, 0.20, and 0.25, respectively. With the addition of nopal mucilage, the peak ru decreased progressively to 0.75 at 10%, placing it in the low susceptibility category, which was reflected in a significant increase in NL (101, 55, and 31 cycles in the three CSR). However, when increased to 12%, ru rose to 0.85, returning to a condition of moderate susceptibility, indicating that excess biopolymer reduced efficacy. In the case of chia mucilage, the best result was achieved at 2%, with an ru of 0.79 and low susceptibility, associated with 74, 40, and 23 cycles in the CSRs, while at higher doses the ru values increased again, classifying them as moderate. Finally, tara gum showed the most outstanding results: at 0.4%, it reached an ru of 0.79 (low susceptibility), with the highest NL values in the entire series, 170, 91, and 52 cycles in the three CSRs. However, when the dose was increased to 0.5% and 0.6%, the ru values rose to 0.87 and 0.91, returning to a moderate level of susceptibility. These results showed that the addition of biopolymers reduced the peak ru compared to natural soil and, therefore, increased resistance to liquefaction, although with a clearly defined optimal dosage range for each additive.

Table 13. Susceptibility to liquefaction

Description / Dosage	r_u peak	Susceptibility
Natural soil 0%	0.98	High
Nopal Mucilage 4%	0.92	Moderate
Nopal Mucilage 6%	0.89	Moderate
Nopal Mucilage 8%	0.81	Moderate
Nopal Mucilage 10%	0.75	Low
Nopal Mucilage12%	0.85	Moderate
Chía Mucilage 1%	0.88	Moderate
Chía Mucilage 1.5%	0.82	Moderate
Chía Mucilage 2%	0.79	Low
Chía Mucilage 2.5%	0.90	Moderate
Chía Mucilage 3%	0.93	Moderate
Tara Gum 0.2%	0.94	Moderate
Tara Gum 0.3%	0.84	Moderate
Tara Gum 0.4%	0.79	Low
Tara Gum 0.5%	0.87	Moderate
Tara Gum 0.6%	0.91	Moderate

Figure 23 shows the variation in peak ru compared to natural soil, which allowed the improvements to be quantified. The untreated soil reached the highest value of 0.98, confirming its high susceptibility. With nopal, the most marked reduction occurred at the 10% dose, where ru fell by 0.23 units, equivalent to a 23.5% decrease compared to natural soil, classifying it as low susceptibility. In chia, the optimal value was 2%, with a ru of 0.79, representing a decrease of 0.19 units or 19.4%, which also placed it in the low susceptibility category. Tara showed the most outstanding performance: at 0.4%, it achieved an ru of 0.79, with a reduction of 0.19 units or 19.4% compared to natural soil, while maintaining the highest number of liquefaction cycles, confirming its superiority. Overall, the graphs showed that all biopolymers managed to reduce the peak ru compared to natural soil, but 0.4% tara established itself as the most effective additive, followed by 10% nopal and 2% chia.

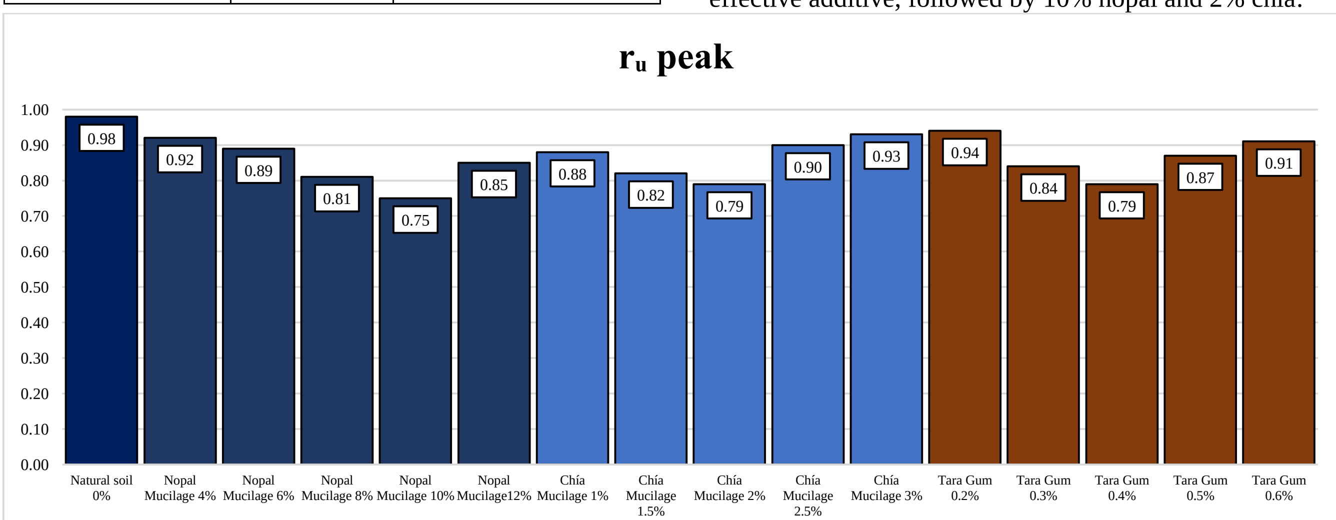

Fig. 23 Susceptibility to liquefaction ru_pico

5. Discussion

In a study conducted in Iran, guar gum and agar gum (0.5%, 1%, and 2%) were used in sandy and silty sand soils. Cohesion increased significantly, reaching up to 684 kPa with 2% agar, while friction angles decreased slightly due to the lubricating effect of hydrogels. Despite this, liquefaction resistance improved considerably, reaching up to 61 cycles at CSR = 0.25 in silty sand [16]. In the present study, similar biopolymers produced comparable trends. Cohesion and bearing capacity increased by 60% and 53%, respectively, with 10% nopal mucilage. The addition of 2% chia mucilage raised liquefaction resistance to 74 cycles at CSR = 0.15, reducing susceptibility to a moderate–low level. Meanwhile, 0.4% tara gum showed the most balanced performance, achieving an effective cohesion of 0.42 kg/cm², a friction angle of around 33°, over 50% improvement in bearing capacity, and more than 60 cycles to liquefaction at CSR = 0.15, with a maximum r_u of 0.80. The main difference lies in the fact that in Iran, work was done with purified industrial gums in low proportions, while in this study, raw plant extracts from nopal, chia, and tara were applied in wider ranges, which led to more moderate increases in cohesion and greater variability in friction angles, although with proven improvements in resistance to liquefaction.

Research conducted in Turkey indicates that the use of Sodium Polyacrylate (SPA), in combination with 25% cement in liquefaction-susceptible sandy soils, leads to an increase in cohesion from zero in the natural state to 24.87 kPa with 5% SPA, although this parameter decreased at higher dosages, while the friction angle improved from 25.6° in the natural soil to 45° with 20% SPA. In addition, permeability with a 15% additive decreased from 0.015 cm/s to 0.012 cm/s, and under high swelling potential, pressures of up to 6.3 kg/cm² were recorded [17]. On the other hand, the natural biopolymers studied exhibited a different behaviour: with 10% nopal mucilage, a 60% increase in cohesion was achieved compared to natural soil; with 2% chia mucilage, a moderate and stable increase was observed; and with 0.4% tara gum, the highest effective cohesion (0.42 kg/cm²) was attained without any tendency to decrease. Unlike SAP, which at higher dosages showed isolated improvements followed by a loss of effectiveness, the nopal, chia, and tara biopolymers demonstrated more consistent performance within their optimal ranges.

In China, it was demonstrated that the addition of a 5% laponite suspension to Hostun sands, after 7 days of curing, improved liquefaction resistance. The number of cycles to liquefaction increased from 22 to 39 at a CSR = 0.14, while also reducing pore pressure build-up, axial strain, and the rate of approach to liquefaction. In physical models, reductions of 49% in tunnel uplift and 57% in surface structure settlement were also reported [19]. In the present study, natural biopolymers likewise exhibited significant improvements: 10% nopal mucilage increased cohesion by 60% and allowable bearing capacity by 53%; 2% chia mucilage achieved 74 cycles prior to liquefaction at CSR = 0.15 with a peak r_u of 0.88; and 0.4% tara gum showed the best overall performance, with an effective cohesion of 0.42 kg/cm², a friction angle of 33°, more than 50% increase in bearing capacity, and over 60 cycles to liquefaction with a peak r_u of 0.80. Unlike laponite, which is a high-performance synthetic nanomaterial, the nopal, chia, and tara biopolymers exhibited lower intensity in terms of mechanical enhancement, but greater eco-efficiency and sustainability due to their local availability.

6. Conclusion

Firstly, the study validated the use of natural biopolymers as a promising and eco-friendly alternative to synthetic additive technologies for the stabilisation of liquefaction-susceptible soils in the Pilcomayo region. It was shown that, regardless of organic variability and the non-industrial nature of the extracts, there was a considerable improvement in shear strength and liquefaction resistance capacity, achieving results comparable to synthetic additives at a lower environmental and economic cost.

Secondly, nopal mucilage was identified as the most significant contributor to soil cohesion. In CU triaxial tests, a 10% nopal mucilage concentration resulted in a 60% increase in cohesion and a 53% increase in allowable bearing capacity compared to the natural soil, despite a slight reduction in the friction angle. In cyclic tests, its performance was more limited: although the number of cycles to liquefaction increased, the maximum reduction was not as efficient as that observed with tara or chia. These results indicate that nopal biopolymer is effective in enhancing static strength and bearing capacity, but less suitable under sustained dynamic loading conditions.

Thirdly, chia mucilage exhibited a notable hydrophobic effect under cyclic testing conditions. With a dosage of 2%, it reached 74 cycles prior to liquefaction at a CSR = 0.15, with a peak r_u of 0.88, thereby reducing soil susceptibility to a moderate–low level. However, in CU triaxial tests, improvements in cohesion and friction angle were lower compared to tara gum and nopal mucilage, indicating reduced overall effectiveness when both static and dynamic resistance are required.

Fourthly, tara gum proved to be the most efficient and well-balanced biopolymer. At an optimal dosage of 0.4%, it achieved an effective cohesion of 0.42 kg/cm² and a friction angle of 33°, representing an increase of over 50% in bearing capacity. Under cyclic conditions, it exceeded 60 cycles to liquefaction at a CSR = 0.15, with a peak r_u of 0.79, without compromising soil stability. This behaviour is attributed to its uniform polymeric structure and its ability to generate continuous interparticle bonding.

Finally, the study enabled the classification of biopolymers based on their performance: tara gum emerged as the most efficient, followed by nopal mucilage, while chia mucilage, although effective under cyclic conditions, exhibited comparatively lower overall performance.

For the specific conditions of the Pilcomayo district characterised by poorly graded sandy soils, shallow groundwater, and seismic activity, the most suitable approach is the use of tara gum at a concentration of 0.4%, complemented by controlled use of nopal where additional cohesion is required.

This strategy provides a comprehensive solution to liquefaction issues, enhancing the safety of both urban and agricultural areas while offering a low environmental impact solution adapted to local conditions.

Conflicts of Interest

For this article, we would like to declare that there are no conflicts of interest.

Sustainability and Data Transparency Statement

The biopolymers used in this research, such as shrinkage-capable nopal mucilage, shrinkage-capable chia mucilage, and tara gum, were obtained from sustainable sources and represent a viable alternative to synthetic stabilisers. Their use is aligned with the principles of sustainable engineering, as they are biodegradable, non-toxic, and contribute to reducing the environmental impacts associated with conventional soil stabilisation methods. The results of this study are based on experimental data obtained under controlled laboratory conditions. Each outcome derives from consistent protocols and direct measurements. The authors can provide the study data upon a duly justified request.

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